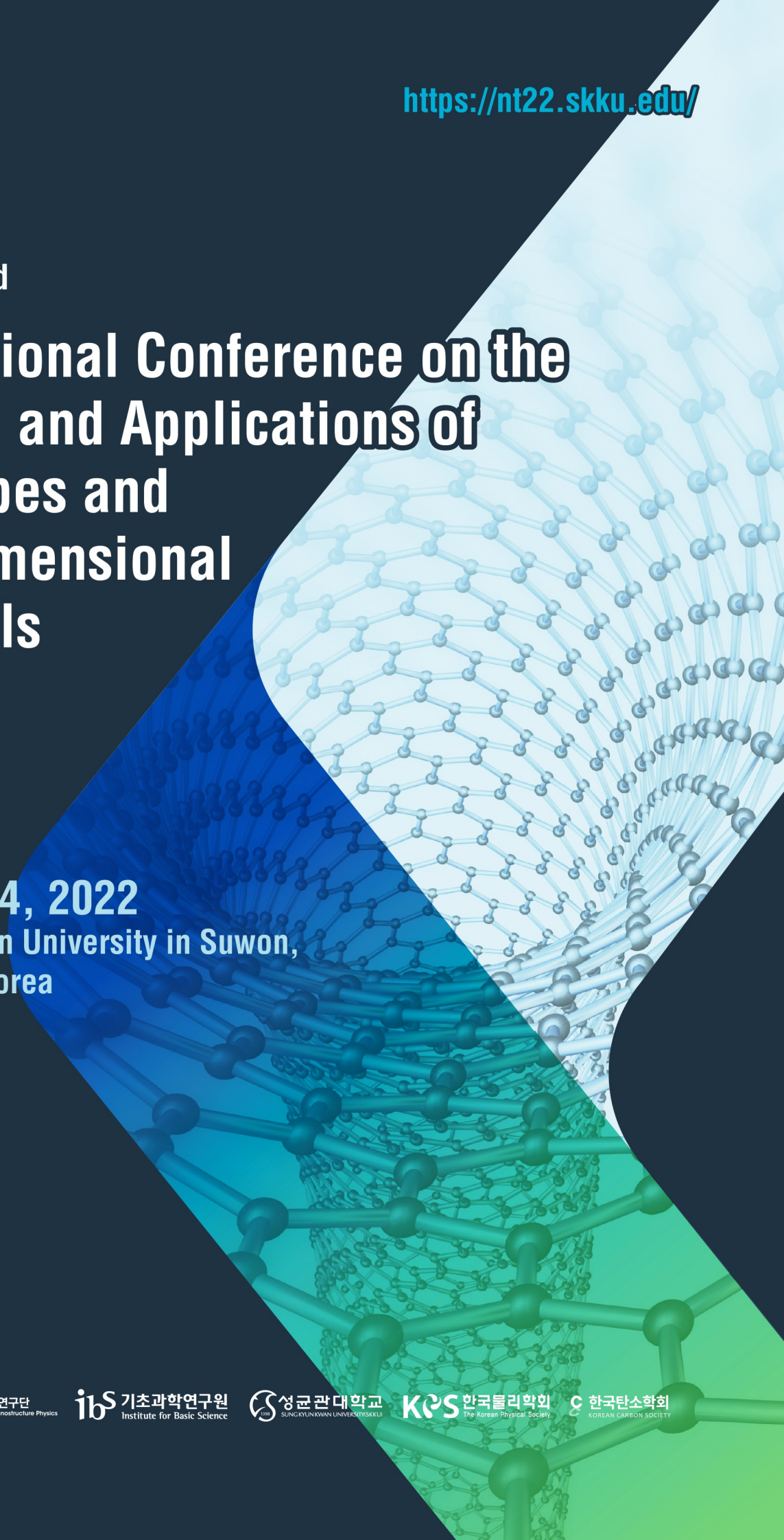
NT22 나노튜브 저차원물질

https://nt22.skku.edu/

The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

June 19-24, 2022

Sungkyunkwan University in Suwon,
Republic of Korea



Cinap 나노구조 물리 연구단 Center for Integrated Nanostructure Physics
ibs 기초과학연구원 Institute for Basic Science
성균관대학교 SUNGKYUNKWAN UNIVERSITY SKKU
KPS 한국물리학회 The Korean Physical Society
한국탄소학회 KOREAN CARBON SOCIETY

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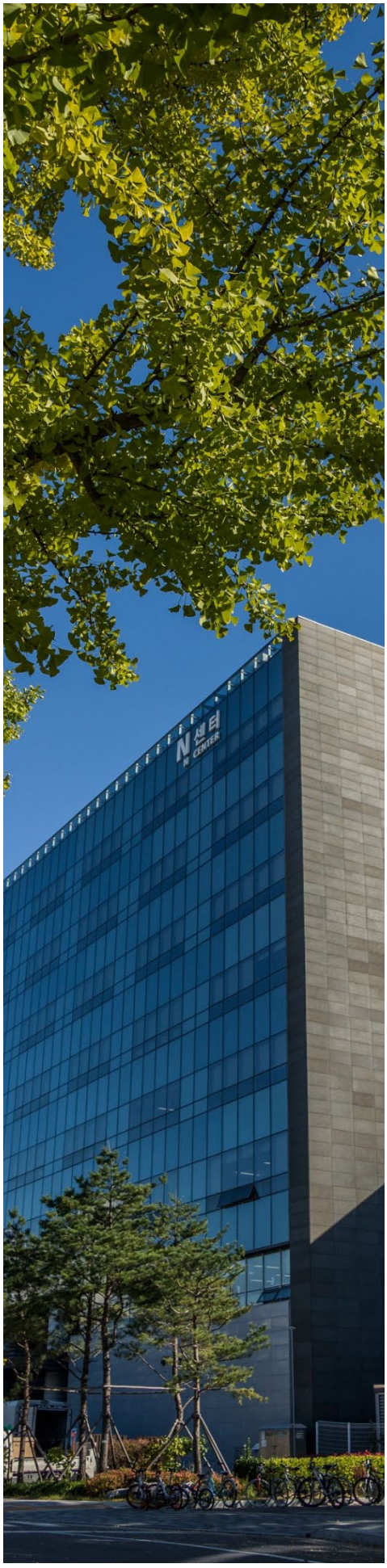

Welcome Message

Since 1999, the International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials (NT) has served as an international stage of discussion for low dimensional material and technology. As the world's top-class conference, Every year over 300 researchers and scientists participate NT to share the most important and latest development in this field. This year NT will be held as a hybrid in-person/virtual events from June 19 to June 24, 2022 at Sungkyunkwan University in Suwon, South Korea.

22nd NT invited the most eminent scientists in carbon nanotube and low dimensional filed; 5 keynote speakers, Prof. Rodney S. Rouff (UNIST), Prof. Phillip Kim (Harvard Univ), Prof. Sarah Haigh (University of Manchester), Prof. Michael S. Arnold(Univ. of Wisconsin-Madison), Prof. Yutaka Ohno (Nagoya Univ.) Also, We have the tutorial session with Prof. Hui Ming Cheng (IMR CAS), Prof. Manish Chhowalla (Univ. of Cambridge), Steven G. Louie (UC Berkeley), many talks by invited speakers and 9 parallel sessions.

Especially, SKKU formed the Industry session so that you can find the opportunity to discuss about the industrial application of low-dimensional materials with experts.

For the successful hosting of the conference, NT22 committee offer the companies and institutions a place which they can build up their global networks. We believe it will be a great opportunity to promote their products and technology for brand amplification and creating new business. We expect your interest and participations.

Young Hee Lee
Chair, Organizing Committee, NT22
Director, IBS Center for Integrated Nanostructure Physics
Professor, Sungkyunkwan University

Organizing Committee

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History

2022 — **June 19-June 24, 2022**
Sungkyunkwan University (SKKU), Suwon, Republic of Korea

2021 — **June 6-June 11, 2021**
ONLINE(Rice University, Houston, Texas, USA)
Online program is active until December 31, 2021

2020 — NT20 was postponed to NT21 due to the pandemic of COVID-19

2019 — **July 21-26, 2019**
Congress Center, Würzburg, Germany

2018 — **July 15-20, 2018**
Peking University, Beijing, China

2017 — **June 25-30, 2017**
Federal University of Minas Gerais - UFMG, Belo Horizonte, Brazil

2016 — **August 7-13, 2016**
University of Vienna, Vienna, Austria

2015 — **June 29-July 3, 2015**
Nagoya University, Nagoya, Japan

2014 — **June 2-6, 2014**
University of Southern California, Los Angeles, California, USA

2013 — **June 24-28, 2013**
Aalto University, Espoo, Finland

2012 — **June 24–29, 2012**
Brisbane Convention & Exhibition Centre, Brisbane, Australia

2011 — **July 10-16, 2011**
University of Cambridge, Cambridge, UK

2010 — **June 27-July 2, 2010**
Hilton Bonaventure Montréal, Canada

2009 — **June 21-26, 2009**
Tsinghua University, Beijing, China

2008 — **June 29 - July 4, 2008**
Le Corum, Montpellier, France

2007 — **June 24-29, 2007**
Parque Metalúrgico - Centro de Artes e Convenções da Universidade Federal de Ouro Preto, Ouro Preto, Minas Gerais, Brazil

2006 — **June 18 - 23, 2006**
Hotel Metropolitan Nagano, Nagano, Japan

2005 — **June 26-July 1, 2005**
Göteborg University, Chalmers University of Technology, and University College of Borås, Göteborg, Sweden

2004 — **July 19-24, 2004**
Hotel Real De Minas, San Luis Potosi, S.L.P., México

2003 — **July 6-11, 2003**
Seoul National University, Seoul, Korea

2001 — **July 22-25, 2001**
Inselhotel Hermannswerder, Potsdam, Germany

1999 — **July 24-27, 1999**
East Lansing, Michigan, USA

Registration

For Check-in, Please note your serial number at 'My page' on the NT22 website

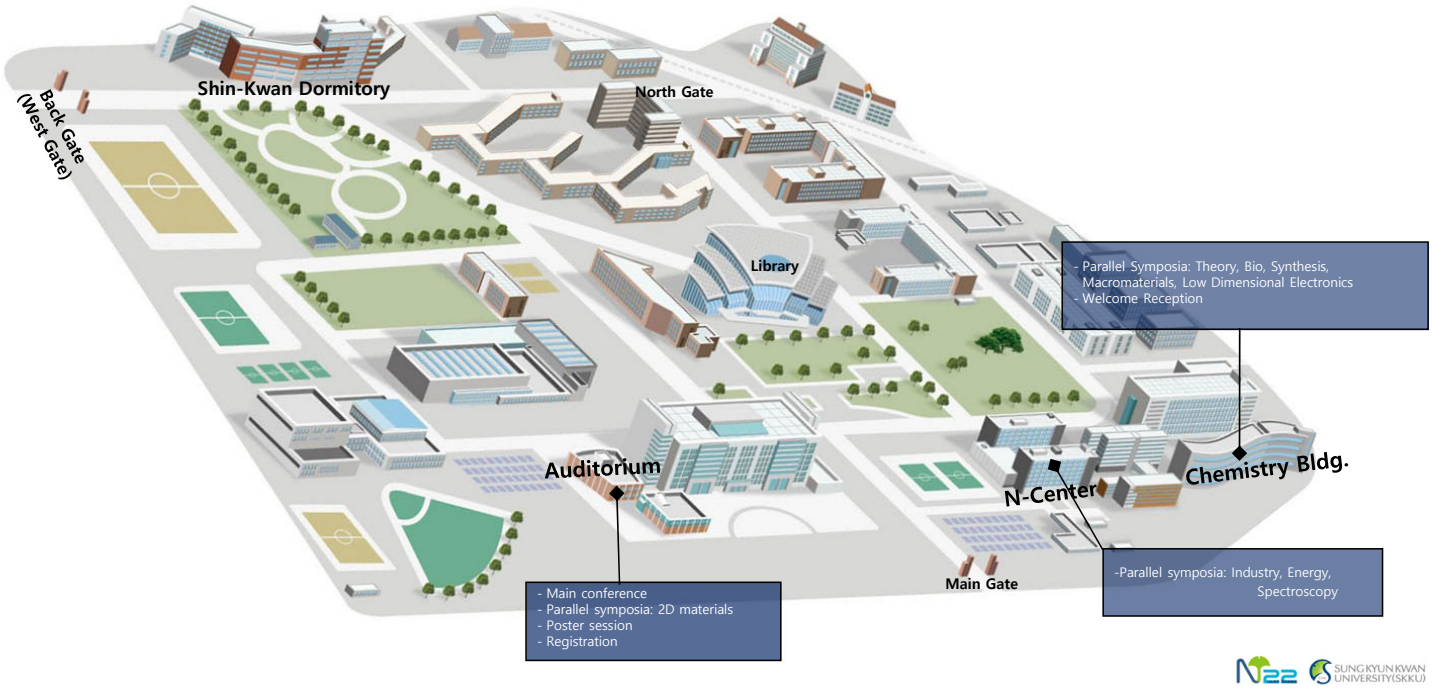
Registration fee includes....

- Admission to all technical sessions
- Coffee breaks
- Welcome reception
- Meal coupons for lunch
- Banquet ticket
- Excursion ticket
  # Advance reservation is necessary within June 20th (Mon)
- Free shuttle bus ticket (Novotel <–> SKKU)
- Program book
- Poster session

At the registration desk,

- Car registrations for parking ticket
- Purchase the additional banquet before Tuesday, June 21st, 2022
- Reserve the excursion within Monday, June 20th, 2022

SKKU map



Meals

- Registration fee includes admission to welcome reception and lunches for 5 days.
- Banquet is included in the registration fee for only regular in-person participants. Companions should additionally purchase a ticket to enter the banquet at the registration desk.

Welcome Reception	• Lobby of Chemistry building • Cafeteria of **Shin-Kwan Dormitory**
Lunch	• Using the meal coupon in name tag • Novotel at Suwon Station
Banquet	• Entry is by the meal coupon only • Additional ticket should be purchased at the registration desk before (Tue) June 21st, 2022

Shuttle bus

The free Sungkyunkwan University(SKKU) shuttle bus service is open to all NT22 participants.

Date	Departure time	Bus stop	Route (From – To)
Sunday June 19, 2022	12:30 pm	Novotel at Suwon Station	Novotel – SKKU
	8:30 pm	SKKU Chemistry building	SKKU – Novotel
Monday June 20, 2022	8:00 am	Novotel	Novotel – SKKU
	1:00 pm	Auditorium (Main conference hall)	SKKU – Novotel
	1:30 pm	Novotel	Novotel – SKKU
	7:00 pm	Auditorium (Main conference hall)	SKKU – Novotel
Tuesday June 21, 2022	8:10 am	Novotel	Novotel – SKKU
	1:00 pm	Auditorium (Main conference hall)	SKKU – Novotel
	1:30 pm	Novotel	Novotel – SKKU
	7:00 pm	Auditorium (Main conference hall)	SKKU – Novotel
Wednesday June 22, 2022	8:10 am	Novotel	Novotel – SKKU
	1:00 pm	Auditorium (Main conference hall)	SKKU – *Korean Folk Village – Novotel *Excursion
	1:30 pm	Auditorium (Main conference hall)	SKKU – Novotel
Thursday June 23, 2022	8:10 am	Novotel	Novotel – SKKU
	1:00 pm	Auditorium (Main conference hall)	SKKU – Novotel
	1:30 pm	Novotel	Novotel – SKKU
	7:00 pm	Auditorium (Main conference hall)	SKKU – Novotel
Friday June 24, 2022	8:10 am	Novotel	Novotel – SKKU
	6:00 pm	Auditorium (Main conference hall)	SKKU – Novotel

Excursion

Korean Folk Village (KFV) was opened to showcase Korean culture to domestic and foreign tourists by collecting in one place the folk customs of our culture that have been inherited for a long time. The Joseon Dynasty Village in KFV is composed of real houses that have been relocated and reconstructed from all over the country, and thus traditional living culture is realized through four seasons based on thorough historical verification and consultation. Presenting experience-style outdoor exhibitions, craft in daily life continuing traditional methods, and seasonal customs are presented.

Advance reservation is necessary!

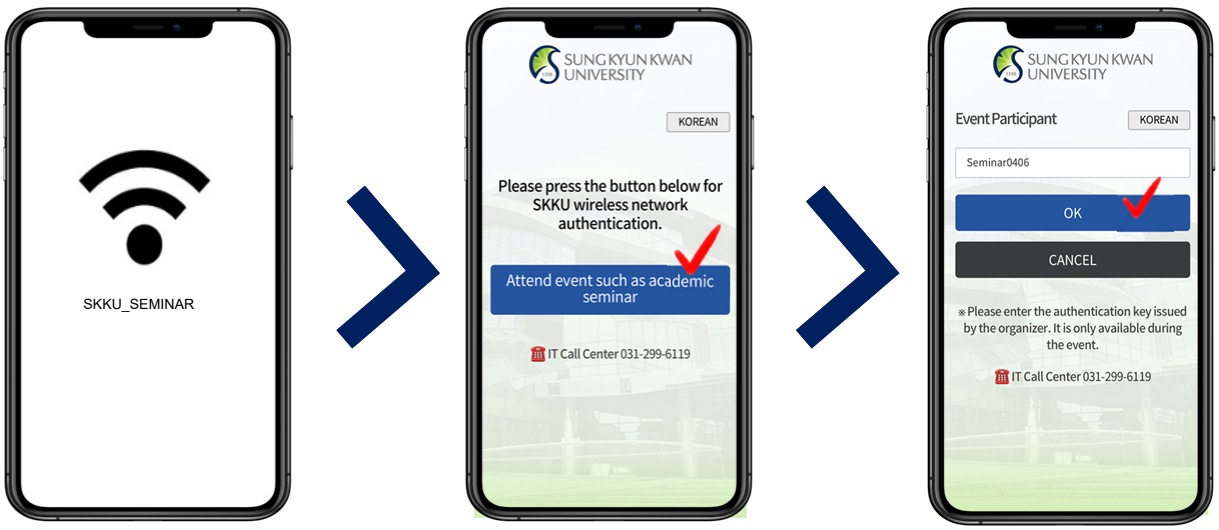
By Monday 20th June

Please come to registration desk and register the limited seat for the shuttle bus to KFV

	Departure time	Bus stop	Route (From – To)
Shuttle Bus Wed. June 22, 2022	1 Pm	Auditorium (Main conference hall)	SKKU – KFV
	5 Pm	KFV	KFV – Novotel (banquet)

* Additional ticket should be purchased at the registration desk within Monday 20th June 2022

Free WIFI



Select Wi-Fi signal
'SKKU_SEMINAR'

Click the button

After filling in
'Seminar0406'
Click the OK button

The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

Conference Schedule at a Glance

Tutorial | Keynote | Invited | Contributed

Main Conference Time Table

Date	June 19th (SUN)	June 20th (MON)	June 21st (TUE)	June 22nd (WED)	June 23rd (THU)	June 24th (FRI)	Date
08:50-09:00		Opening					08:50-09:00
09:00-09:50		Rodney Ruoff	Philip Kim	Yutaka Ohno	Michael Arnold	Sarah Haigh	09:00-09:50
09:50-10:10		Ksenia Bets	Esko Kauppinen	Youfan Hu	James Elliott	Daniel A. Heller	09:50-10:10
10:10-10:20							10:10-10:20
10:20-10:30		Yan Li	Hyeonsik Cheong	(c) Micah Green	Yuichiro Kato	Xuedan Ma	10:20-10:30
10:30-10:40							10:30-10:40
10:40-10:50				Coffee break			10:40-10:50
10:50-11:00		Coffee break	Coffee break		Coffee break	Coffee break	10:50-11:00
11:00-11:10				(c) Cheol Jin Lee			11:00-11:10
11:10-11:20		Emmanuel Flahaut	Ado Jorio		Benjamin S. Flavel	Seokwoo Jeon	11:10-11:20
11:20-11:40				Stephanie Reich (Recorded)			11:20-11:40
11:40-11:50		(c) Feng Ding	(c) Katalin Kamaras		(c) Martin Koehne	(c) Katsutoshi Hori	11:40-11:50
11:50-12:00				Lunch			11:50-12:00
12:00-13:00		Lunch	Lunch		Lunch	Lunch	12:00-13:00
13:00-13:15				Ncenter Tour			13:00-13:15
13:15-13:30		Poster 1	Poster 3	Advance reservation is necessary	Poster 5	Parallel symposia	13:15-13:30
14:00-14:30	Manish Chhowalla			Excursion			14:00-14:30
14:30-15:15		Parallel symposia	Parallel symposia		Parallel symposia		14:30-15:15
15:15-15:45	Huiming Cheng						15:15-15:45
15:45-16:00						Coffee break	15:45-16:00
16:00-16:30						Sergei Tretiak	16:00-16:30
16:30-16:45	Coffee break					(c) Nicola Curreli	16:30-16:45
16:45-16:50	FORUM						16:45-16:50
16:50-17:00						Poster award & Closing ceremony	16:50-17:00
17:00-17:15	Current challenges and future perspectives in low dimensional materials	Coffee break	Coffee break		Coffee break		17:00-17:15
17:15-17:30		Poster 2	Poster 4		Poster 6		17:15-17:30
17:45-18:00							17:45-18:00
18:00-18:30	Welcome reception			Conference banquet			18:00-18:30
18:30-20:30							18:30-21:00

Parallel Symposia Time Table

Venue		Auditorium Room 701129	N Center Room 86120			Chemistry Building Room 330102	Chemistry Building Room 330110		Chemistry Building Room 330118		Venue
Date	**Time**	**2D material**	**Industry**	**Spectroscopy**	**Energy**	**Low D electronics**	**Theory**	**Bio**	**Synthesis**	**Macromaterials**	**Time**
Mon JUNE 20	**14:30-15:00**		Mitsugu Uejima			Chul-Ho Lee	Christophe Bichara		Shigeo Maruyama		**14:30-15:00**
	15:00-15:30		Peiyu Sun			Jang Ung Park	Qinghong Yuan		Sofie Cambré		**15:00-15:30**
	15:30-15:40	**Short Break**									**15:30-15:40**
	15:40-16:10		Hakmin Lee			Yang Chai	Jeil Jung		Jaegeun Lee		**15:40-16:10**
	16:10-16:40		Taneli Juntunen			Yanqing Wu	Mikito Koshino		Yuan Chen		**16:10-16:40**
	16:40-17:00		(c) Hee Jin Jeong			(c) Haomin Wang	(c) Youngkuk Kim		(c) Miguel Vazquez-Pufleau		**16:40-17:00**

Venue		Auditorium Room 701129	N Center Room 86120			Chemistry Building Room 330102	Chemistry Building Room 330110		Chemistry Building Room 330118		Venue
Date	**Time**	**2D material**	**Industry**	**Spectroscopy**	**Energy**	**Low D electronics**	**Theory**	**Bio**	**Synthesis**	**Macromaterials**	**Time**
TUE JUNE 21	**14:30-15:00**	Lain-Jong Li		Sebastian Heeg		Sanghoon Bae	Hyoung Joon Choi		Jing Kong		**14:30-15:00**
	15:00-15:30	Kibum Kang		Kaihui Liu		Albert G. Nasibulin	Ting Cao		Wencai Ren		**15:00-15:30**
	15:30-15:40	**Short Break**									**15:30-15:40**
	15:40-16:00	Jong-Hyun Ahn		Sang-Yong Ju		Chuanhong Jin	Alister Page		(c) Byeong Wook Cho		**15:40-16:10**
	16:00-16:10								(c) Soo Ho Choi		**16:00-16:10**
	16:10-16:20	Jiaxing Huang		Laura Kim		Kosuke Nagashio	(c) Daniel Hedman				**16:10-16:20**
	16:20-16:30								Qingwen Li		**16:20-16:30**
	16:30-16:40						(c) Tenta Tani				**16:30-16:40**
	16:40-16:50	(c) Pilkyung Moon		(c) Ji-Hee Kim		(c) Tzu-Ang Chao					**16:40-16:50**
	16:50-17:00										**16:50-17:00**

Parallel Symposia Time Table

Venue		Auditorium Room 701129	N Center Room 86120			Chemistry Building Room 330102	Chemistry Building Room 330110		Chemistry Building Room 330118		Venue
Date	**Time**	**2D material**	**Industry**	**Spectroscopy**	**Energy**	**Low D electronics**	**Theory**	**Bio**	**Synthesis**	**Macromaterials**	**Time**
THU JUNE 23	**14:30-15:00**	Xinran Wang			Jong Beom Baek	Jana Zaumseil		Yutaka Majima		John Bulmer	**14:30-15:00**
	15:00-15:30	Hyeon Suk Shin			Michael De Volder	Dmitri Golberg		Laurent Cognet		Bon-Cheol Ku	**15:00-15:30**
	15:30-15:40	**Short Break**									**15:30-15:40**
	15:40-16:10	Vincent Tung			Fei Wei	Shinpei Ogawa		Gili Bisker		Changsik Song	**15:40-16:10**
	16:10-16:30	(c) Sayyed Sajjadi			Morinobu Endo	Gregory Pitner		Jong-Ho Kim		Alexander Balandin	**16:10-16:30**
	16:30-16:40	(c) Young seo Jeon									**16:30-16:40**
	16:40-16:50				(c) Yoonbin Kim	Harri Lipsanen		(c) Sanghwa Jeong		(c) Cristina Madrona	**16:40-16:50**
	16:50-17:00										**16:50-17:00**
	17:00-17:10										**17:00-17:10**

Venue		Auditorium Room 701129	N Center Room 86120			Chemistry Building Room 330102	Chemistry Building Room 330110		Chemistry Building Room 330118		Venue
Date	**Time**	**2D material**	**Industry**	**Spectroscopy**	**Energy**	**Low D electronics**	**Theory**	**Bio**	**Synthesis**	**Macromaterials**	**Time**
FRI JUNE 24	**13:15-13:35**	Clément FAUGERAS			Hyoyoung Lee	(c) Arindam Bala		Markita Landry		Milo Shaffer	**13:15-13:35**
	13:35-13:45					Jeff Blackburn					**13:35-13:45**
	13:45-14:05	Christoph STAMPFER			Hong Jin Fan			(c) Nicole Iverson		Philippe Poulin	**13:45-14:05**
	14:05-14:15					**Short Break**		(c) Chaejeong Heo			**14:05-14:15**
	14:15-14:25	**Short Break**			**Short Break**					**Short Break**	**14:15-14:25**
	14:25-14:35	Guillaume CASSABOIS			(c) Dimitrios Perivoliotis	(c) Patrick Edwards		**Short Break**		Geoff Wehmeyer	**14:25-14:45**
	14:35-14:45							(c) Mijin Kim			**14:35-14:45**
	14:45-14:55				(c) Mariam Ezzedine	(c) Vikram Deshpande					**14:45-14:55**
	14:55-15:05	(c) Naoto Nakatsuji						Tae-il Kim		Dmitry Rybkovskiy	**14:55-15:05**
	15:05-15:15										**15:05-15:15**
	15:15-15:25	(c) Mohammed Alamri									**15:15-15:25**
	15:25-15:35									(c) Bharath Natarajan	**15:25-15:35**
	15:35-15:45										**15:35-15:45**

The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

Main Conference Program & Abstract

Tutorial Session **Auditorium**

Sunday, JUNE 19th, 2022

14:00 - 15:15	T2	Chair: Hyeonjin Shin (SAIT) **Manish Chhowalla** (University of Cambridge, UK) *Tutorial on metallic two-dimensional transition metal dichalcogenides and their applications in electrochemistry*
15:15-16:30	T3	Chair: Kikang Kim (Sungkyunkwan University) **Hui-Ming Cheng** (IMR CAS, China) *Low-dimensional materials towards global mission of carbon neutrality*
16:30-16:45	Coffee break	
16:45-18:00		Chair: Young Hee Lee (Sungkyunkwan University) **FORUM** *Current challenges and future perspectives in low dimensional materials*
18:00-20:30	Welcome reception	

Many-body Interaction and Topological Phenomena in One- and Two-dimensional Materials

Steven G. Louie
Physics Department, University of California at Berkeley, and LBNL
Berkeley, California 94720 USA
sglouie@berkeley.edu

In this talk, I present some recent theoretical progress in understanding and predicting quantum phenomena in atomically thin one- and two-dimensional materials. Many-body interaction, symmetry, and topological effects in these systems have led to the manifestation of a number of interesting and unexpected behaviors. Several examples will be discussed. Strong electron-electron and electron-hole interactions give rise to the existence of: strongly bounded correlated multiparticle excitations (in additional to excitons), such as trions and biexcitons; novel moiré excitons in twisted bilayer heterostructures; universal slow yet tunable plasmons; giant excitonic enhancement of shift currents (a nonlinear optical effect) in non-centrosymmetric 2D semiconductors; and remarkable many-electron features in field-driven, time-resolved and angle-resolved photoemission spectroscopy (tr-ARPES), among others. Topological considerations lead to novel optical transition selection rules owing to a heretofore unrecognized invariant in 2D semiconductors. Another theoretical discovery is that distinct topological phases exist in graphene nanoribbons (GNRs). Junctions between topological distinct GNRs are predicted to support robust in-gap topologically protected junction states that can be used for band engineering. Experimental realizations of many of the theoretical findings have been achieved. The occurrence of such abundance of novel phenomena due to interaction and topological effects adds to the promise of atomically thin 2D materials for exploration of new science and valuable applications.

Tutorial on metallic two-dimensional transition metal dichalcogenides and their applications in electrochemistry

Manish Chhowalla
University of Cambridge
Materials Science & Metallurgy
mc209@cam.ac.uk

I will start with a brief description of the different phases of 2D transition metal dichalcogenides. Our previous work has shown that compact electrodes assembled from monolayered nanosheets of metallic 1T phase MoS_2 are highly conductive, lyophilic, and are catalytically active. I will briefly describe the different phases of 2D MoS_2 and their catalytic properties – focusing on the role of sulfur vacancies and strain. Here we report the realization of high-performance lithium-sulfur batteries using metallic 1T phase of two-dimensional molybdenum disulfide as binder-free conducting cathodes for hosting sulfur. The attributes of metallic 2D MoS_2 lead to > 85% utilization of sulfur due to improved adsorption of lithium polysulfides, enhanced Li^+ diffusivity, accelerated electrochemical reaction kinetics and superior electrocatalytic activity for polysulfide conversion. We have translated these properties into practical pouch cells, achieving areal capacities of 8.21 ± 0.07 mAh cm^{-2} and capacity retention in excess of 85% over 200 cycles. The metallic MoS_2-based ampere-hour-scale (1.3 ± 0.05 Ah) pouch cells can deliver gravimetric energy density of 402 Wh kg^{-1} and volumetric energy density of 721 Wh L^{-1}. These metrics compare exceptionally favourably with current state-of-the-art in Li-S batteries. Our results provide unique insights into new designs for Li-S cathodes based on electrocatalytically active and conducting two-dimensional (2D) materials.

Low-dimensional materials towards global mission of carbon neutrality

Hui-Ming Cheng[1, 2]
[1] *Faculty of Materials Science and Engineering, Institute of Technology for Carbon Neutrality, Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China*
[2] *Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang, China*
Email: hm.cheng@siat.ac.cn

The carbon neutrality has become the global mission for the sustainable development of mankind. The development of new energy and environment-friendly materials is fundamental to achieve carbon neutrality. Low-dimensional materials have unique properties such as high surface area, unique physical, chemical, and electronic properties. Therefore, it is highly desirable to make use of low-dimensional materials towards global mission of carbon neutrality.

Herein, we highlight the recent advances of developing low-dimensional materials towards global mission of carbon neutrality mainly based on the research work in our group. As shown in Fig. 1, first, we introduce new material development and carbon neutrality. Then, the applications of low-dimensional materials in carbon neutrality are highlighted. Among them, the achievements and challenges of renewable energy (especially solar energy), energy conversion (green hydrogen energy), energy storage (Li-S batteries, Li-CO_2 batteries, micro-supercapacitors, and battery recycling) are introduced. We expect that this presentation would be beneficial for improving the overall knowledge on low-dimensional materials, aiming at advance the global mission of achieving carbon neutrality.

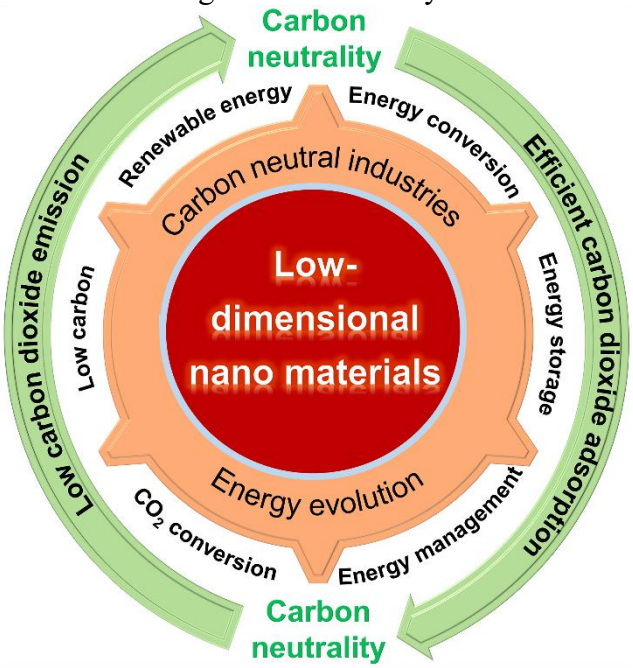


Fig 1. Schematic of low-dimensional materials towards global mission of carbon neutrality

Main Session		Auditorium
Monday, JUNE 20th, 2022		
08:50-09:00	Opening	
09:00-09:50	Keynote	Chair: Seunghyun Baik (Sungkyunkwan University) **Rodney Ruoff** (UNIST & IBS Center for Multidimensional Carbon Materials) *Dissolving, and growing, diamond; Protonation of diamondoids; Large area single crystal metal foils and their use to make F-Diamane and 'perfect' single crystal large area graphene; Zeolite Templated Carbons (Schwartzites)*
09:50-10:20	Invited I1	**Ksenia Bets** (Rice University, USA) *Lateral epitaxy of 2D materials and its practical applications*
10:20-10:50	I2	**Yan Li** (Peking University, China) *Behavior of catalysts at atomic scale for single-walled carbon nanotube growth*
10:50-11:10	Coffee break	
11:10-11:40	I3	Chair: Christophe Bichara (CNRS) **Emmanuel Flahaut** (CNRS, France) *Surface chemistry and its influence on the environmental impact of carbon nanomaterials*
11:40-12:00	Contributed Talk C1	**Feng Ding** (IBS Center for Multidimensional Carbon Materials, Korea) *Why carbon nanotube grow?*
12:00-13:15	Lunch @ 'Shin-Kwan' Dormitory	
13:15-14:30	P1	Poster Session 1 @ Auditorium
14:30-17:00	Parallel Symposia	
17:00-17:15	Coffee break	
17:15-18:30	P2	Poster Session 2 @ Auditorium

Main Session **Auditorium**

Dissolving, and growing, diamond; Protonation of diamondoids; Large area single crystal metal foils and their use to make F-Diamane *and* 'perfect' single crystal large area graphene; Zeolite Templated Carbons (Schwartzites)

Rodney S. Ruoff[a,b]

[a]Center for Multidimensional Carbon Materials (CMCM), Institute for Basic Science (IBS), Ulsan, Republic of Korea; [b]Department of Chemistry, Department of Materials Science, School of Energy and Chemical Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan, Republic of Korea

ruofflab@gmail.com, rsruoff@ibs.re.kr, ruoff@unist.ac.kr

(i). We recently reported our discovery of several kinetics regimes for dissolution of single crystal diamond (with (100) or (110) surface orientations) into 500-nm thick nickel or cobalt films [1a]. Dissolution is driven by a concentration gradient where the [C] in the Ni or Co is highest at the metal/ diamond interface, and lowest at the free Ni or Co surface, and where C diffusing to this free surface is removed by reaction with water vapor. (ii) The calculated proton affinity (PA) and gas phase basicity (GPB) of diamondoids from adamantane to large diamondoids such as with 131 carbon atoms have been calculated and recently reported along with other properties such as the distribution of excess positive charge throughout the protonated product cations [2]. I'll also discuss our experimental efforts to achieve protonation of diamondoids contacting diamantane, triamantane, and certain isomers of tetramantane and pentamantane, with carborane acids. Carborane acids are the strongest acids known and their conjugate bases are exceptionally non-reactive. (iii). An overview of our conversion of as-received commercial, polycrystalline copper foils to single crystal Cu(111) foils [3] and their use to generate single crystal Cu/Ni(111) foils [4a, 4b] that allow making single crystal AB-stacked bilayer graphene [5] is briefly given, and we thus turn to (iv) conversion of AB-stacked bilayer graphene to F-diamane [6], and (v) use of Cu/Ni(111) foils to generate large area, single crystal, graphene that has no adlayers or folds or wrinkles [7]. *Support from the Institute for Basic Science (IBS-R019-D1) is appreciated.*

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Lateral epitaxy of 2D materials and its practical applications

Ksenia V. Bets*, Qiyuan Ruan, Boris I. Yakobson

Rice University, Houston, TX 77005, USA

Ksenia.Bets@rice.edu

Despite several decades of intense research, the scalable and well-controlled growth of high-quality monocrystalline 2D materials largely remains unachieved. The use of well-developed techniques and methods of classical 3D growth allowed for rapid initial success in low dimensional synthesis relying on structural matching between the substrate and target material. However, over the years, it became clear that the transition from 3D to 2D materials required modification of the methodology that had to start with a deeper understanding of underlying principles. Due to their nature, most 2D materials have minimal plane-to-plane interaction with the underlying substrate making orientation control a difficult task. Luckily, virtually no substrate surface is ever defect-free, presenting new opportunities for growth control. We have demonstrated that interaction between 2D material edge and substrate surface steps and kinks plays a crucial role in the nucleation and orientation of growing material [1]. Furthermore, we formulated geometric complementarity principles that ensure the large-scale defect-free growth of 2D materials.

Unlike many 2D materials, the growth of borophene is plagued by the precisely opposite issue – too strong interaction with the substrate. The metal substrates stabilize the growth of 2D structure due to the strong binding with boron atoms but at the same time prevent subsequent borophene exfoliation hindering its practical applications. On the other hand, the low-interacting substrates typically do not provide sufficient areal interaction resulting in significant nucleation barrier or formation of 3D clusters. Following principles of lateral epitaxy of 2D material, we propose a dimensionality reduction technique relying on nucleation on naturally present 1D surface defects [2]. On the example of the h-BN substrate, we demonstrate an order of magnitude reduction in the nucleation barrier due to covalent bonding to the exposed substrate steps while maintaining minimal areal adhesion. This approach not only exemplifies the importance of the lateral epitaxy mechanism in the growth of 2D materials but also provides a practical approach to the synthesis of novel nanomaterials.

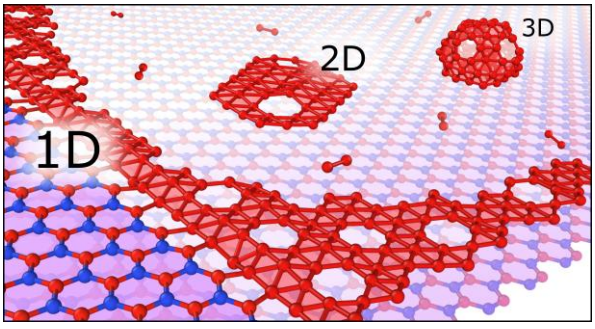

Fig 1. Dimensionality reduction in borophene growth

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Behavior of catalysts at atomic scale for single-walled carbon nanotube growth

Yan Li

College of Chemistry and Molecular Engineering, Peking University, Beijing 100871, China

yanli@pku.edu.cn

Catalysts play important roles in the chemical vapor deposition of single-walled carbon nanotubes (SWCNTs). The difference of intermetallic Co_7W_6 catalysts and mono-metallic catalysts have been previously reported. Electron microscopic techniques, particularly the *in-situ* techniques enable us to study the growth mechanism and compare the behavior of catalysts at atomic scale. We found that the growth of SWCNTs by Co catalysts associates to the partial carbonization of catalysts as well as carbon dissolving and precipitation (Figure 1). However, the Co_7W_6 nanocrystals were stable at the temperature of 1100 °C under carbon feeding condition and no carbon dispersion within the nanocrystal happened (Figure 2). Due to the less efficient carbon diffusion and supply on the surface of catalysts than that in a vapor-liquid-solid process, SWCNTs normally nucleate on larger catalyst nanocrystals in vapor-solid-solid process. These results can help us to further understand the mechanism of the selective growth of SWCNTs, benefiting the rational design of catalysts.

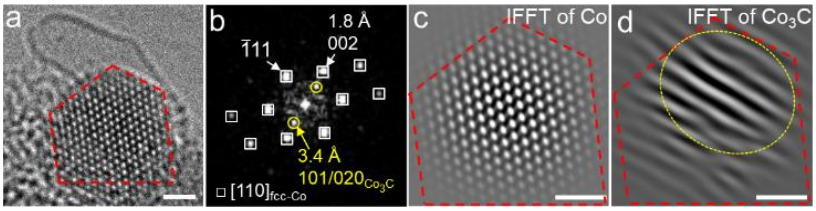

Fig 1. Distribution of Co_3C species in Co catalysts. a, Single shot high-resolution ETEM image showing a SWCNT nucleating on cobalt catalyst acquired at 600 °C. b, FFT of the particle region marked by dashes in (a). c-d, IFFT formed using spots of Co (c) and Co_3C (d) in corresponding FFT. Region of Co_3C crystalline was roughly marked by circle in (d).

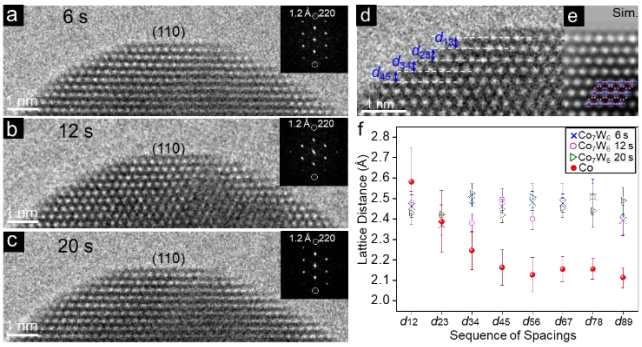

Figure 5. **Quantitative analysis of lattice spacings of Co_7W_6 and Co at the reactive environment**. **a**–**c**, Time-resolved HRTEM images of a close up view of Co_7W_6 nanoparticle at 1000 °C in CO (101 Pa). Inset, corresponding FFT patterns. **d**, Determination of the position of individual atomic columns by 2D Gaussian fitting. The sequence of spacings are labeled as d_{12}, d_{23}, d_{34}… from surface to core. **e**, Simulated HRTEM image based on the atomic model of Co_7W_6 along the [10 $\bar{1}0$ $\bar{1}$] orientation (immerged). **f**, The Co_7W_6 (110) lattice spacings at different exposure time to CO at 1000 °C. Error bars were calculated from the standard deviation of the mean lattice parameters among 6-10 individual measurements for a given atomic shell. The ($1\bar{1}\bar{1}$) lattice spacings of fcc Co at 700 °C in CH_4/H_2 (v/v=7/3, 49 Pa) were included for comparison

Surface chemistry and its influence on the environmental impact of carbon nanomaterials

E. Flahaut[a], P. Braylé[b], L. Evariste[b], G. Caorsi[c], F. Candotto Carniel[c], A-M. Galibert[a], B. Soula[a], L. Ballerini[d], M. Tretiach[c], M. Barret[b], E. Pinelli[b], F. Mouchet[b], L. Gauthier[b]

[a] Centre Interuniversitaire de Recherche et d'Ingénierie des Matériaux, Université Paul Sabatier, CIRIMAT UMR CNRS, INPT, UPS N°5085, Toulouse, France

[b] EcoLab, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France

[c] Department of Life Sciences, University of Trieste, Italy

[d] Neuron Physiology and Technology Lab, SISSA, Trieste, Italy

emmanuel.flahaut@univ-tlse3.fr

Carbon nanomaterials (and especially carbon nanotubes) are often cited first when people are asked about "nanoparticles" in general. For some people, they represent a huge potential of applications due to their extraordinary properties (or maybe more realistically because of their unique combination of different properties), while some others will mention first the (potential) related toxicity and environmental impact issues – on which we will focus here.

We will quickly review different aspects related to the potential environmental toxicity of carbon nanomaterials and will summarize our main results in this field. In particular, we have identified that the impact of carbon nanomaterials with very different morphologies ranging from zero-D (nanodiamonds) to 2D (few-layer graphene, graphene oxide) can be generalized when the metric used for the comparison of the data is the surface (m^2/L) instead of the weight (g/L) [1].

We will mainly discuss here about the specific case of graphene oxide (GO) to show how the modification of surface chemistry (reduction) can be used to transform GO into rGO and thus significantly decrease the risk during handling and use, in a "safer(r) by design" strategy. Examples will be taken from our work within the framework of the Graphene Flagship EU project to illustrate how a mild thermal reduction of GO can fully remove the toxicity towards environmental species such as amphibians [2], algae, bacteria [3] or plants [4] – or modify its impact on other species such as zebrafish embryos [5].

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Why carbon nanotube grow?

Liping Ding, Ben Mclean, Ziwei Xu, Feng Ding

Center for Multidimensional Carbon Materials (CMCM), Institute for Basic Science (IBS), Ulsan 44919, Republic of Korea

School of Materials Science and Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, Republic of Korea

f.ding@unist.ac.kr

Three decades of intense research effort has been dedicated to understanding the growth of carbon nanotubes (CNTs) since Sumio Iijima's famous discovery in 1991 (Nature 354, 56–58 (1991)). It is thus a great surprise that the most fundamental question "why do carbon nanotubes grow?" has puzzled the field for 30 years. Without answering this key question, the ultimate goal of controllable CNT growth is unattainable.

We propose a solution to this most fundamental and challenging problem. Our manuscript explains, for the first time, what makes a graphitic carbon cap lift off a catalyst nanoparticle to grow a CNT rather than adhere and encapsulate it. Using accurate first principles and molecular dynamics calculations, we show the strong SWCNT edge-catalyst interaction, which is up to 6-9 eV/nm, is contact angle dependent. When this SWCNT edge-catalyst interaction overcomes the cap-catalyst adhesion, a CNT can grow.

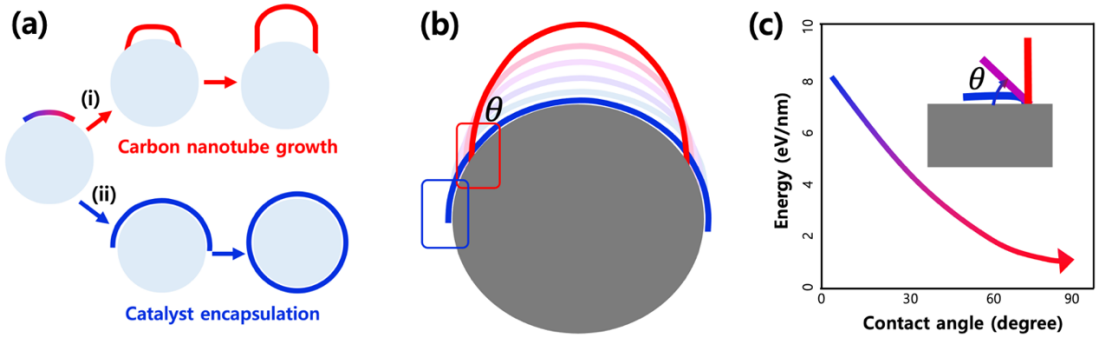

FIG. (a) two possible routes for the evolution of a graphitic carbon cap on a surface of a catalyst particle: (i) lift of the graphitic carbon into a graphitic cap and subsequent CNT growth; (ii) continuous growth of the graphitic carbon to surround the catalyst particle finally resulting in catalyst encapsulation. It is apparent that the final state of route (ii) is energetically more favourable because of the adhesion between graphitic carbon and the catalyst surface. Then why do CNTs grow? (b) the lifting of a graphitic cap leads to an increase in the contact angle between the edge of the graphitic carbon and the catalyst surface from zero. (c) the increase of the contact angle leads to a significant decrease in the energy and, thus, drives the CNTs growth.

Main Session **Auditorium**

Tuesday, JUNE 21st, 2022

Chair: Junichiro Kono (Rice University)

09:00-09:50 Keynote K2 **Philip Kim** (Harvard University, USA)
Electrical and Thermal Transport in Nanotube-Graphene Hybrid Systems

09:50-10:20 I10 **Esko Kauppinen** (Aalto University School of Science, Finland)
Towards SWNT (n,m) structure control during floating catalyst CVD synthesis

10:20-10:50 I5 **Hyeonsik Cheong** (Sogang University, Korea)
Optical spectroscopy of twisted heterostructures of transition metal dichalcogenides

10:50-11:10 Coffee break

Chair: Hyeon Suk Shin (UNIST)

11:10-11:40 I6 **Ado Jorio** (Universidade Federal de Minas Gerais, Brazil)
Tip-enhanced Raman Spectroscopy in Low Dimensional Carbon Materials: graphene, nanoflakes and carbon nanotubes

11:40-12:00 C2 **Katalin Kamaras** (IBS Center for Multidimensional Carbon Materials, Korea)
Near-field infrared microscopy and spectroscopy on nanotubes: structure, metallicity, and quasiparticles on the nanoscale

12:00-13:15 Lunch @ 'Shin-Kwan' Dormitory

13:15-14:30 P3 Poster Session 3 @ Auditorium

14:30-17:00 Parallel Symposia

17:00-17:15 Coffee break

17:15-18:30 P4 Poster Session 4 @ Auditorium

Electrical and Thermal Transport in Nanotube-Graphene Hybrid Systems

Philip Kim
Department of Physics, Harvard University
Cambridge MA -2138, USA
pkim@physics.harvard.edu

In low-dimensional systems, the combination of reduced dimensionality, strong interactions and topology has led to a growing number of many-body quantum phenomena. In this talk, we will discuss electrical and thermal transport across low-dimensional graphitic conductors. In the first part, we discuss Coulomb drag between an individual single-walled carbon nanotube (SWNT) as a one-dimensional (1D) conductor and the two-dimensional (2D) conductor monolayer graphene, separated by a few-atom-thick boron nitride layer. Here, the graphene carrier density is tuned across the charge neutrality point (CNP) by a gate, while the SWNT remains degenerate. At high temperatures, the drag resistance changes sign across the CNP, as expected for momentum transfer from drive to drag layer, and exhibits layer exchange Onsager reciprocity. We find that layer reciprocity is broken near the graphene CNP at low temperatures due to nonlinear drag response associated with temperature dependent drag and thermoelectric effects. The drag resistance shows power-law dependences on temperature and carrier density characteristic of 1D Fermi liquid-2D Dirac fluid drag. The 2D drag signal at high temperatures decays with distance from the 1D source slower than expected for a diffusive current distribution, suggesting additional interaction effects in the graphene in the hydrodynamic transport regime. In the second example, we measured non-local voltage fluctuations in a multi-terminal graphene device to reveal the electronic heat transported across a mesoscopic bridge made of carbon nanotubes. Using two-dimensional graphene as a noise thermometer, we measured the quantitative electronic thermal conductance of graphene and carbon nanotubes up to 70 K, achieving a precision of ~1% of the thermal conductance quantum at 5 K. Employing linear and nonlinear thermal transport, we observed signatures of energy transport mediated by long-range interactions in SWNTs, in agreement with a theoretical model.

Towards SWNT (n,m) structure control during floating catalyst CVD synthesis

Esko I. Kauppinen

Department of Applied Physics, Aalto University School of Science, Espoo, Finland

Floating-catalyst CVD (FC-CVD) is a highly promising technique for the scalable synthesis of single-walled carbon nanotubes (SWNTs), especially for the direct deposition SWNT thin films for flexible electronics applications. We have been studying FC-CVD systems with several carbon precursor molecules, including CO, C_2H_4, CH_4, ethanol, methanol, isopropanol, and toluene, using mainly iron catalyst nanoparticles, either generated in-situ via ferrocene vapor thermal decomposition or pre-made via the spark discharge aerosol generator. We have determined the SWNT atomic structure i.e. (n,m) distributions directly via the electron diffraction of individual tubes supported by the optical absorption spectroscopy studies. Using ferrocene as the catalyst precursor, CO as the carbon source and CO_2 as the growth promoter, we show that the SWNT (n,m) distribution and the related thin film color can be directly tuned by adjusting the CO_2 concentration. Also, the fraction of metallic tubes can be tuned via adding carbon dioxide. We will present results on the synthesis of mainly semiconducting tubes from ethanol via adding methanol, and also from isopropanol as the carbon source when using nitrogen carrier gas with minor fraction of hydrogen as the carrier gas. The chiral angle distributions from both CO and ethanol are biased towards the armchair side, while those from hydrocarbons are rather flat. Finally, we will present mechanistic studies addressing the activity of the catalysts on both ferrocene as well as spark generated based systems.

Optical spectroscopy of twisted heterostructures of transition metal dichalcogenides

Hyeonsik Cheong
Department of Physics, Sogang University
35 Baekbeom-ro, Mapo-gu, Seoul 04107, Korea
hcheong@sogang.ac.kr

The heterostructures consisting of monolayers of transition metal dichalcogenides (TMDs) have been extensively studied as the alignment of the bands in the constituent materials allow for manipulation of optoelectronic and transport properties. The band offset between the bands has been considered to be the most important parameter in determining the physical properties of these structures. However, as evidenced in the so-called 'magic-angle graphene' [1], the twist angle between the crystallographic directions of the two layers is an important parameter that affect the physical properties. As the twist angle between two layers of a given set of materials is varied, the moiré periodicity changes. The additional periodicity imposed by the moiré superlattice modifies the overall translational symmetry of the system, and as a result, the phonon spectrum as well as the electronic band structure, and the optoelectronic properties of the heterostructure change systematically. Furthermore, at very small twist angles, atomic-scale lattice reconstruction [2] has been observed in many homo-bilayers and heterostructures and should be accounted for in describing the physical properties of the heterostructures. In this talk, I will present some of the latest experimental data on the phonon spectra and the band structures from twisted heterostructures of different combination of TMDs.

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[2] Yoo H., *et al*., Nature Materials (2019), **18**, 448.

Tip-enhanced Raman Spectroscopy in Low Dimensional Carbon Materials: graphene, nanoflakes and carbon nanotubes

Ado Jorio
Departamento de Física, Universidade Federal de Minas Gerais
Av. Antonio Carlos 6627, Campus Pampulha, Belo Horizonte, MG, Brazil
adojorio@fisica.ufmg.br

In this talk I will discuss our recent developments on nano-Raman spectroscopy characterization of low-dimensional carbon nanostructures. The nano-Raman spectroscopy is implemented utilizing the tip-enhanced Raman spectroscopy technique. We have studied carbon nanotubes, graphene single and multilayers, twisted bilayer graphene and graphene nano-flakes. Different aspects related to these systems will be addressed, especially the local phonons and electron-phonon signatures that appear when measuring reconstructed low-angle twisted bilayer graphene [1].

[1] AC Gadelha et al., Nature 590, 405-409 (2021)

Near-field infrared microscopy and spectroscopy on nanotubes: structure, metallicity and quasiparticles on the nanoscale

Katalin Kamarás[a], Gergely Németh[a], Dániel Datz[a], Áron Pekker[a], Ferenc Borondics[b], Keigo Otsuka[c], Kate E. Walker[d], Graham A. Rance[d], Andrei N. Khlobystov[d], Shigeo Maruyama[c]

[a] *Wigner Research Centre for Physics, 1525 Budapest, Hungary*

[b] *Synchrotron SOLEIL, L'Orme des Merisiers, 91192 Gif Sur Yvette CEDEX, France*

[c] *Department of Mechanical Engineering, The University of Tokyo, Tokyo 113-8656, Japan*

[d] *School of Chemistry, University of Nottingham, Nottingham NG7 2RD, United Kingdom;*

kamaras.katalin@wigner.hu

Optical imaging of nanotubes on the individual tube level in the infrared range promises a wealth of information: electronic type (metallic or semiconducting), defect detection, and identification of encapsulated species. We use scattering-type scanning near-field optical microscopy (s-SNOM) with two infrared lasers and a spectroscopy setup in the tunable range (spectral regions 960 – 1020 and 1320 – 1450 cm^{-1}), to extract optical information with effective spatial resolution of a few nanometers. The spectral range can be extended by using infrared synchrotron radiation. The s-SNOM method is based on a metal-clad atomic force microscope tip, the outgoing signal contains both topographic and optical scattering information. Collective excitations, e.g. free electron absorption or polariton modes, can be easily detected, but for individual molecular vibrations the sensitivity is low, unless they are coupled to a collective mode. Such modes can be phonon-polaritons (e.g. in boron nitride nanotubes) or plasmon-polaritons (in carbon nanotubes or graphene). With the appropriate coupling mechanism, chemical reactions between encapsulated species can be followed.

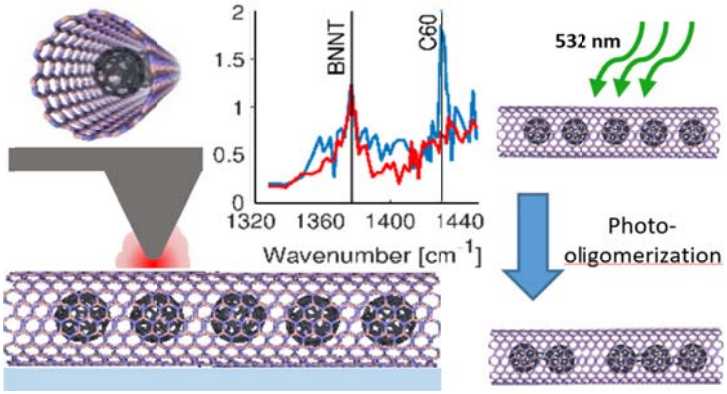

Figure 1. Left: s-SNOM measurement of C_{60}@BNNT showing spectral lines of both C_{60} and BNNT phonon modes. Right: In situ oligomerization of fullerene molecules inside BNNT; the products can be identified by their specific vibrations in the s-SNOM spectra [4].

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Main Session **Auditorium**

Wednesday, JUNE 22nd, 2022

		Chair: Manish Chhowalla (University of Cambridge)
09:00-09:50	Keynote K3	**Yutaka Ohno** (Nagoya University, Japan) *Carbon nanotube analog-digital mixed-signal integrated circuits for epidermal electronics*
09:50-10:20	I7	**Youfan Hu** (Peking University, China) *Carbon nanotube-based epidermal electronic systems*
10:20-10:40	C3	**Micah Green** (Texas A&M University, USA) *Additive Manufacturing of Thermosetting Resins via Radio Frequency Heating of Carbon Nanotubes*
10:40-11:00	Coffee break	
		Chair: Jong-Hyun Ahn (Yonsei University)
11:00-11:20	C4	**Cheol Jin Lee** (Korea University, Korea) *High performance cold cathode X-ray tubes based on CNT field electron emitter*
11:20-11:50	I8	**Stephanie Reich** (Freie Universitaet Berlin, Germany) *Raman scattering by exciton-polaritons in carbon nanotubes*
11:50-13:00	Lunch @ 'Shin-Kwan' Dormitory	
13:00-13:30	Ncenter Tour (Advance reservation is necessary)	
13:30-18:00	**Excursion**	
18:00-21:00	Banquet @ Novotel hotel	

Carbon nanotube analog-digital mixed-signal integrated circuits for epidermal electronics

Yutaka Ohno
Institute of Materials and Systems for Sustainability, Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
yohno@nagoya-u.jp

Epidermal electronics that can be mounted directly onto human skin to monitor biological signals have wide applicability, such as in healthcare and sports. This requires integrating various analog and analog-digital mixed-signal circuits such as amplifiers and an analog/digital converter (ADC) on a flexible film as well as sensors. A low operating voltage is also essential for epidermal electronics to accommodate safety concerns and a limited power supply.

Because carbon nanotube (CNT) thin-film transistors (TFTs) fabricated on a flexible plastic film have relatively high mobility and excellent mechanical flexibility, they may help realise low-voltage flexible electronics for wearable devices. However, the electrical characteristics of CNT TFTs often have large device-to-device variability because of the randomness of the network-like CNT thin film. This can significantly degrade the performance and increase the operating voltage of CNT-based circuits compared to the ideal case. In addition, CNT TFTs often exhibit instability issues such as hysteresis and threshold voltage drift under a bias stress, which seriously impact stability of analog circuits.

In this work, we address these issues for realizing a low-voltage and fully flexible analog-digital mixed-signal circuits based on CNT TFTs. The key contribution is a novel operational amplifier with a high gain and low operating voltage, which can configure negative-feedback circuits and dramatically suppresses the influence of device-to-device variability and instability. Fully flexible CNT-based mixed-signal circuits were realised monolithically on a plastic film and demonstrated stable and continuous operation at a low supply voltage of ±1.5 V. A flexible delta-sigma ADC with high energy efficiency was also realised. A fully flexible analog-frontend circuit, which is the most important circuit for sensors, demonstrated stable and continuous operation during the amplification and digitalisation of electrocardiogram (ECG) signals.

Carbon nanotube-based epidermal electronic systems

Youfan Hu

Key Laboratory for the Physics and Chemistry of Nanodevices, Center for Carbon-Based Electronics, and School of Electronics, Peking University, Beijing 100871, China

youfanhu@pku.edu.cn

Epidermal systems that offer conformal contact with biological surfaces for physiological information capture is of great interest in various applications toward advanced forms of monitoring, diagnosis and therapy. In general, an intimate interface is required between the electronic system and the biological tissue to guarantee a stable signal recording with high fidelity. Here we show several examples of our recent progress to construct such epidermal systems for physiological information monitoring from human body surface, which integrate flexible sensors, carbon nanotube based circuits and memory, demonstrating a great possibility of next-generation wearables for personal health care.

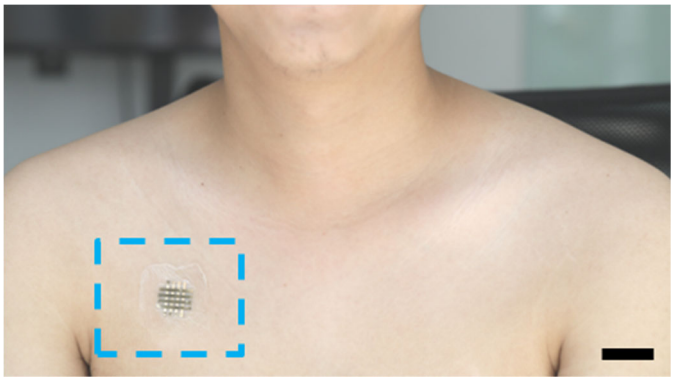

Fig. 1 Epidermal system for capturing physiological information from body surface.

Additive Manufacturing of Thermosetting Resins via Radio Frequency Heating of Carbon Nanotubes

Micah J. Green
Texas A&M University
3122 TAMU 200, College Station, TX, USA
micah.green@tamu.edu

Direct Ink Writing (DIW) is an extrusion-based additive manufacturing method where the print medium is a liquid-phase 'ink' dispensed out of small nozzles and deposited along digitally defined paths. Conventional DIW methods for thermosetting resins rely on the use of viscosifiers, novel crosslinking chemistries, and/or long curing schedules in an oven. Here, we demonstrate the use of a co-planar radio frequency applicator to generate an electric field which can be used to rapidly heat and cure DIW-printed, nanotube-filled composite resins. This method avoids the need of an oven or post-curing step. The proposed process consists of a layer-by-layer, print-and-cure cycle which allows for printing of high-resolution, multi-layer structures. Every extruded layer is partially cured using RF before depositing the next layer; this allows the printed part to maintain structural integrity without buckling under its own weight. The process enables both increased throughput and decreased touch time relative to traditional part manufacturing. Commercial epoxy resin with varied nanotube loadings were examined as DIW candidates. Rheological characterization was used to assess both curing kinetics and printing behavior. After printing, the thermo-mechanical properties, surface finish, and shape retention of RF-cured samples were evaluated and found to be comparable against samples conventionally cured in an oven. This method of manufacturing establishes RF heating as a suitable alternative to conventional methods, facilitating rapid, free-form processing of thermosetting resins without a mold.

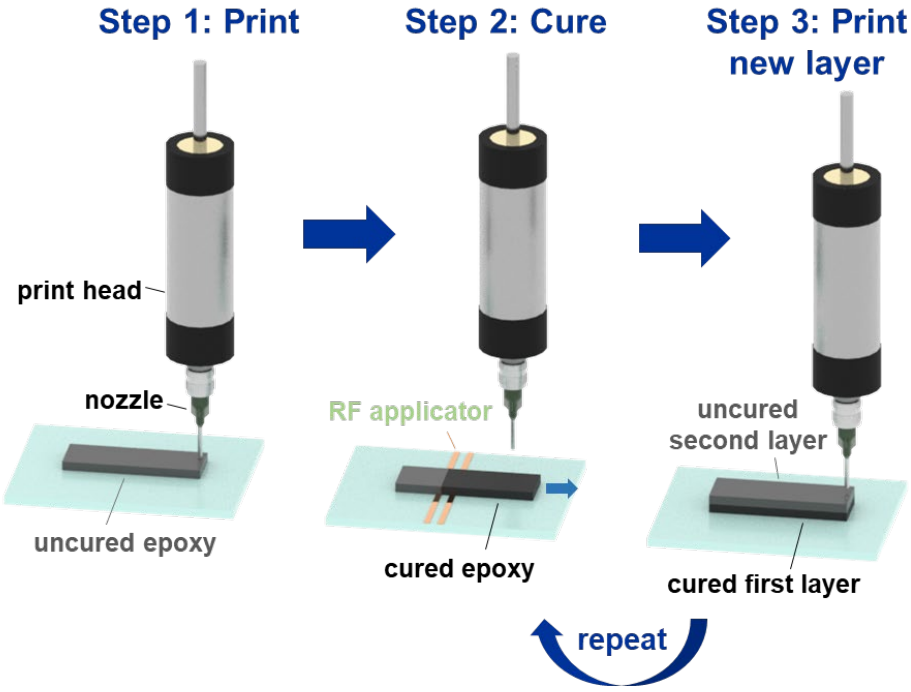

Figure 1. Nanotube-loaded epoxy resin can be printed and locally cured using radio frequency (RF) heating of the carbon nanotubes.

High performance cold cathode X-ray tubes based on CNT field electron emitter

Hyunjea Lee[b], Jun Soo Han[a], Han Bin Go[a], Si Eun Han[a] and Cheol Jin Lee[a, b*]

[a]*School of Electrical Engineering, Korea University, Seoul 136-713, South Korea*
[b]*Dobong Nanotech, Seoul 02841, Korea*

[*]*Corresponding author: cjlee@korea.ac.kr*

The cold cathode x-ray tube was fabricated using a carbon nanotube (CNT) field electron emitter made by a free-standing CNT film. The cold cathode x-ray tubes indicate not only a high tube current but also an extremely high tube current density.[1] It is understood that the high tube current density is caused by an CNT field emitter which has a lot of emission sites at the edge of CNT film. In addition, it shows a high electron beam transmittance and a small focal spot size due to optimized geometries of the gate and the focusing lens.[2,3] The CNT cold cathode x-ray tube also indicates good lifetime during 120,000 shots. After all, high performance of cold cathode X-ray tubes is attributed to an ensemble of the CNT field electron emitter using thin CNT film, the gate with a slit, and the unique focusing lens with a curve-shape elliptical geometry. The proposed cold cathode X-ray tube can enlarge a realm of X-ray applications not only for medical diagnosis systems but also for non-destructive analysis systems and security check systems in the future.

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Raman scattering by exciton-polaritons in carbon nanotubes

Georgy Gordeev, Patryk Kusch, Stephanie Reich
Freie Universitaet Berlin
Arnimallee 14, 14195 Berlin, Germany
stephanie.reich@fu-berlin.de

Benjamin Flavel
Karlsruhe Institute of Technology, Karslruhe, Germany

Eduardo B. Barros
Federal University of Ceará, Fortaleza, Brazil

Resonant Raman scattering has been used for decades to study single walled carbon nanotubes (CNTs), but lacks a consistent theory that simultaneously explains all characteristic signatures. We argue that a proper description requires introducing exciton polaritons as couples excitonic and photonic states. We describe the polaritons by waveguided theory for a nanometre thick cylinder with modified dielectric function. During their propagation along the tube, the polaritons scatter with phonons and are re-emitted as photons with smaller energy (Stokes scattering event). This approach consistently explains the energetic positions of the Raman resonances for the radial-breathing mode (RBM), the G and the 2D line as well as the asymmetry in the scattering intensity of the incoming and outgoing resonances without resorting to higher-order scattering events. We measured the Raman effect on chirality-sorted nanotubes over the first and second exciton resonance and excellently predict its behaviour, which has not been achieved before. The formation of polaritonic states will affect other optical processes in CNTs. Furthermore, exciton-polariton effects appear inevitable in all one-dimensional excitonic systems, similar to our observations in single walled carbon nanotubes.

Main Session **Auditorium**

Thursday, JUNE 23rd, 2022

		Chair: Shigeo Maruyama (University of Tokyo)
09:00-09:50	Keynote K4	**Michael Arnold** (University of Wisconsin-Madison, USA) *Organizing and Growing Semiconducting Carbon*
09:50-10:20	I9	**James Elliott** (University of Cambridge, USA) *Highly Oriented Direct-Spun Carbon Nanotube Textiles Aligned by In-Situ Radio-Frequency Fields*
10:20-10:50	I4	**Yuichiro Kato** (RIKEN Tokyo, Japan) *Exciton physics and cavity quantum electrodynamics in air-suspended carbon nanotubes*
10:50-11:10	Coffee break	
		Chair: Laurent Cognet (University of Bordeaux & CNRS)
11:10-11:40	I11	**Benjamin S. Flavel** (KIT, Germany) *Global Alignment of Carbon Nanotubes via High Precision Microfluidic Dead-End Filtration*
11:40-12:00	C5	**Martin Koehne** (Robert Bosch GmbH, Germany) *Intercalation of aluminium chloride in graphene sheets boosts electrical conductivity to 20 MS/m*
12:00-13:15	Lunch @ 'Shin-Kwan' Dormitory	
13:15-14:30	P5	Poster Session 5 @ Auditorium
14:30-17:00	Parallel Symposia	
17:00-17:15	Coffee break	
17:15-18:30	P6	Poster Session 6 @ Auditorium

Organizing and Growing Semiconducting Carbon

Michael S. Arnold

University of Wisconsin-Madison

Semiconducting carbon nanotubes and graphene nanoribbons have enormous potential in next-generation semiconductor electronics. However, they have been inhibited by major challenges in synthesis and organization. This presentation will highlight advances in (1) the self-assembly of semiconducting carbon nanotubes via two-dimensional liquid-crystalline interactions at fluid-fluid interfaces[1]; (2) the bottom-up anisotropic synthesis of semiconducting graphene nanoribbons (Fig. 1) on Ge and Ge on Si substrates from polycyclic aromatic hydrocarbon molecular seeds and methane[2]; and, (3) field-effect transistors (FETs) fabricated from these materials. The use of atomically thin materials with faceted edges to direct the self-assembly of block copolymers via a new mechanism called boundary-directed epitaxy[3] will also briefly be discussed.

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2. A.J. Way, et al., Graphene nanoribbons initiated from molecularly derived seeds. *Nature Communications*, In Press (2022).

3. R.M. Jacobberger, et al., Boundary-directed epitaxy of block copolymers, *Nature Communications*, 10.1038/s41467-020-17938-3 (2020).

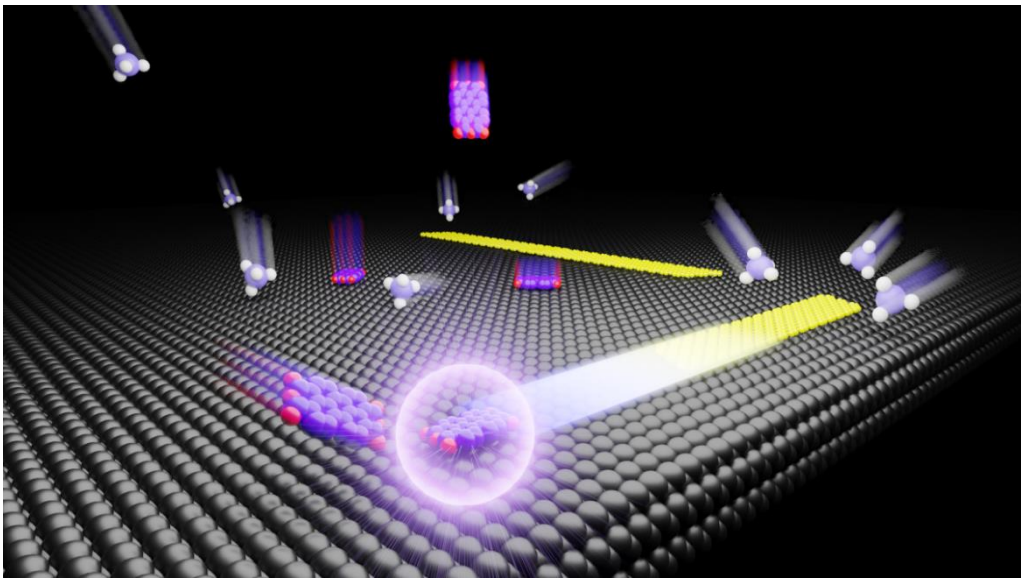

Fig. 1. Synthesis of armchair semiconducting graphene nanoribbons starting from molecular seeds based on polycyclic aromatic hydrocarbons (purple and red molecules) and then selectively extended via CH_4 chemical vapor deposition (CVD).

Highly Oriented Direct-Spun Carbon Nanotube Textiles Aligned by In-Situ Radio-Frequency Fields

James A. Elliott
Department of Materials Science & Metallurgy, University of Cambridge, 27 Charles Babbage Road, Cambridge, CB3 0FS, United Kingdom.
jae1001@cam.ac.uk

Carbon nanotube (CNT) fibers synthesized using a wide variety of different processes show a strong correlation between the alignment of CNTs and physical properties such as strength and conductivity [1]. The alignment of CNTs can occur at both the bundle-level and between different bundles, and is usually quantified using order parameters defined from X-ray diffraction and electron microscopy measurements [2]. Previous attempts to increase fiber alignment during synthesis by application of DC electric fields have been unsuccessful due to the excessively high field strengths required to achieve sufficient orientation for relatively flexible CNTs under synthesis conditions in a chemical vapor deposition tube furnace reactor [3]. In this work, we describe a more recent success using AC fields applied in situ during floating catalyst synthesis to continuously align CNTs during the formation of CNT bundles and subsequent aerogel [4]. A mesoscale model developed to simulate the alignment process shows that the main reason for success of AC fields is the effective stiffening of CNTs through a “z-pinch” effect. The resulting bulk CNT textiles demonstrated an increase in the specific electrical and tensile properties (up to 90 and 460%, respectively) without modifying the quantity or quality of the constituent CNTs. Such methods show great promise for improving the quality of CNT textiles in continuous manufacturing processes.

References

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[3] Philipp Kloza, James A. Elliott *Macromol. Theory Simulations* 2020, **29** (6), 2000049. https://doi.org/10.1002/MATS.202000049.
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Exciton physics and cavity quantum electrodynamics in air-suspended carbon nanotubes

Y. K. Kato [a, b]
[a] *Nanoscale Quantum Photonics Laboratory, RIKEN Cluster for Pioneering Research, Saitama 351-0198, Japan*
[b] *Quantum Optoelectronics Research Team, RIKEN Center for Advanced Photonics, Saitama 351-0198, Japan*
yuichiro.kato@riken.jp

Electron-hole pairs form tightly-bound excitons in carbon nanotubes due to limited screening of the Coulomb interaction, and these stable excitonic states play a central role in the optical processes. Here we discuss unique excitonic phenomena in pristine air-suspended carbon nanotubes, where the intrinsic properties of excitons can be investigated. The mobile excitons exhibit long diffusion lengths [1], and in combination with the increased scaling due to one-dimensionality, efficient exciton-exciton annihilation leads to antibunching at room temperature [2]. There exist excitonic fine structures within the large binding energy, many of which are dark states with optical transitions forbidden by spin, momentum, and parity selection rules. By studying the dynamics and diffusion properties of the bright excitons and the even-parity dark excitons, we find that more than half of the dark excitons can be transformed into the bright excitons [3]. Silicon photonic crystal nanobeam cavities can be used to induce cavity quantum electrodynamical effects [4], and we take advantage of the Purcell enhanced decay rate to obtain the radiative quantum efficiency of bright excitons [5]. With high-efficiency light emission and single-photon generation capabilities, carbon nanotubes offer new opportunities in nanoscale quantum photonics.

Work partly supported by MIC (SCOPE 191503001) and JSPS (KAKENHI JP20H02558).

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Global Alignment of Carbon Nanotubes *via* High Precision Microfluidic Dead-End Filtration

Christian Rust [a,b], Han Li [a], Georgy Gordeev [c], Manuel Spari [a], Markus Guttmann [d], Qihao Jin [e], Stephanie Reich [c] & Benjamin S. Flavel [a]

[a] *Institute of Nanotechnology, Karlsruhe Institute of Technology, Germany.*
[b] *Institute of Materials Science, Technische Universität Darmstadt, Germany.*
[c] *Department of Physics, Freie Universität Berlin, Germany.*
[d] *Institute of Microstructure Technology, Karlsruhe Institute of Technology, Germany.*
[e] *Light Technology Institute, Karlsruhe Institute of Technology, Germany.*
benjamin.flavel@kit.edu

In order to better understand the global alignment of carbon nanotubes by 'slow filtration', precise filtration control and accurate *in-situ* measurement of carbon nanotube film formation are required. In our work, we use a calibrated positive pressure microfluidic dead-end filtration setup which is capable of *in-situ* measurement of the transmembrane pressure, volume rate and membrane retention. This allows us to vary the volume rate of filtration with high accuracy ($\pm$1.7 µL min^{-1} at 100 µL min^{-1}) and identify regimes associated with the formation of SWCNT crystallites or their global alignment but also to understand the importance of each step to the filtration process. These alignment regimes are then discussed in terms of membrane fouling and the interaction potential between the surface of the membrane and nanotubes. Single wall carbon nanotubes dispersed by negatively charged sodium deoxycholate (DOC) or positively charged cetrimonium bromide (CTAB) are shown to assemble into aligned films (3.8 cm²) on polycarbonate membranes. Global alignment ($S_{2D\ max} \approx 0.85$) is obtained on both pristine polyvinylpyrrolidone (PVP) coated membranes and those with an intentional 150 nm – 600 nm groove pattern from hot-embossing.

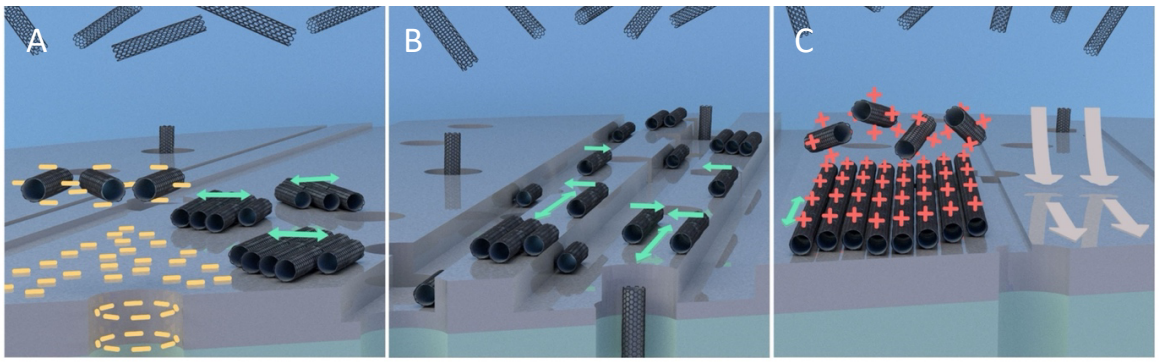

Fig. 1. Illustration of the alignment of (A) DOC dispersed SWCNTs on a pristine PVP coated membrane, (B) a hot embossed membrane and (C) CTAB dispersed SWCNTs on an untextured membrane. The beige arrows indicate shear flow parallel to the membrane which acts as an alignment director for the SWCNTs.

Intercalation of aluminium chloride in graphene sheets boosts electrical conductivity to 20 MS/m

Martin Köhne
Department of Advanced Technologies and Micro Systems, Robert Bosch GmbH, 71272 Renningen, Germany
martin.koehne@de.bosch.com

The intercalation of various compounds in graphite is well-known [1] as well as the strong influence of the Lewis acidity of the intercalant on the electrical conductivity of the intercalated graphite [2]. Bach et al. intercalated aluminium chloride ($AlCl_3$) in highly ordered graphite. The high Lewis acidity of $AlCl_3$ allows to attract electrons from the graphite. This can be considered as an extrinsic p-type doping which increases the electrical conductivity up to 15.9 MS/m [3].

I will present the results for graphene sheets doped with $AlCl_3$ as well as co-doped with $AlCl_3$ and $AuCl_3$. The graphene sheets show in comparison to Bach et al. a higher electrical conductivity up to 20 MS/m and are still so flexible that bending is possible.

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Main Session **Auditorium**

Friday, JUNE 24th, 2022

		Chair: Jana Zaumseil (University Hedelberg)
09:00-09:50	Keynote K5	**Sarah Haigh** (University of Manchester, UK) *Atomic Imaging in Liquid Environments using 2D material heterostructures*
09:50-10:20	I12	**Daniel A. Heller** (Memorial Sloan Kettering Cancer Center, USA) *Carbon Nanotubes for Cancer Research and Diagnosis*
10:20-10:50	I13	**Xuedan Ma** (Argonne National Laboratory, USA) *Developing Quantum Photon Sources from Low-dimensional Semiconductor Materials*
10:50-11:10	Coffee break	
		Chair: Kikang Kim (Sungkyunkwan University)
11:10-11:40	I14	**Seokwoo Jeon** (KAIST, Korea) *Broad Applications using Graphene Quantum Dots with Discrete Bandgap*
11:40-12:00	C6	**Katsutoshi Hori** (Nagoya University, Japan) *Degradation of Carbon Nanotubes in the Presence of Bacterial Enzymes*
12:00-13:15	Lunch @ 'Shin-Kwan' Dormitory	
13:15-15:45	Parallel Symposia	
15:45-16:00	Coffee break	
		Chair: Ji-Hee Kim (Sungkyunkwan University)
16:00-16:30	I15	**Sergei Tretiak** (Los Alamos National Laboratory, USA) *Theoretical Insight into New Strategies of Carbon Nanotube Functionalization*
16:30-16:50	C7	**Nicola Curreli** (Italian Institute of Technology, Italy) *Control of Electronic Band Profiles by Depletion Layer Engineering in Core-Shell Metal Oxide Nanocrystals*
16:50-17:30	Poster award & Closing ceremony @ Auditorium	

Atomic Imaging in Liquid Environments using 2D material heterostructures

S J Haigh[1]*, N. Clark[1], Y Zou[1], D Kelly[1], R Gorbachev[1]

University of Manchester

1. National Graphene Institute, University of Manchester, Oxford Road, M13 9PL, sarah.haigh@manchester.ac.uk

Nanomaterials have driven huge scientific innovation in computing, communications, energy, transportation and healthcare. This rapid progress has only been possible due to innovative characterization methods, which allow visualization, control and optimization of structure at the nanoscale. Transmission electron microscopy (TEM) is an essential characterization technique enabling nanomaterials development, yet most TEM is performed with the sample exposed to high vacuum, an environment that is not compatible with most chemical reaction conditions, physical processes or biological structures. Commercial in-situ liquid cell TEM imaging holders often prevent atomic resolution imaging and chemical analysis. Building on 2D nanochannel technology (Fig. 1b)[3]. We have pioneered a new approach to in-situ imaging that does not compromise the TEM's atomic resolution or analytical capabilities by using 2D materials to encapsulate the controlled reaction environment. The in-situ 2D heterostructure liquid cell approach makes it possible to study the earliest stage of chemical synthesis and adatom motion at the atomic scale [1,2]; something that was not previously possible by any technique (Fig. 1a). The 2D heterostructure approach also enables study of 2D materials chemical degradation in different environments (e.g. CrBr3, GaSe, black phosphorus) (Fig. 1c)[4] and a route to understanding the changes in atom/ion motion at interfaces where the 2D materials are twisted with respect to each other (Fig. 1d).[5,6]

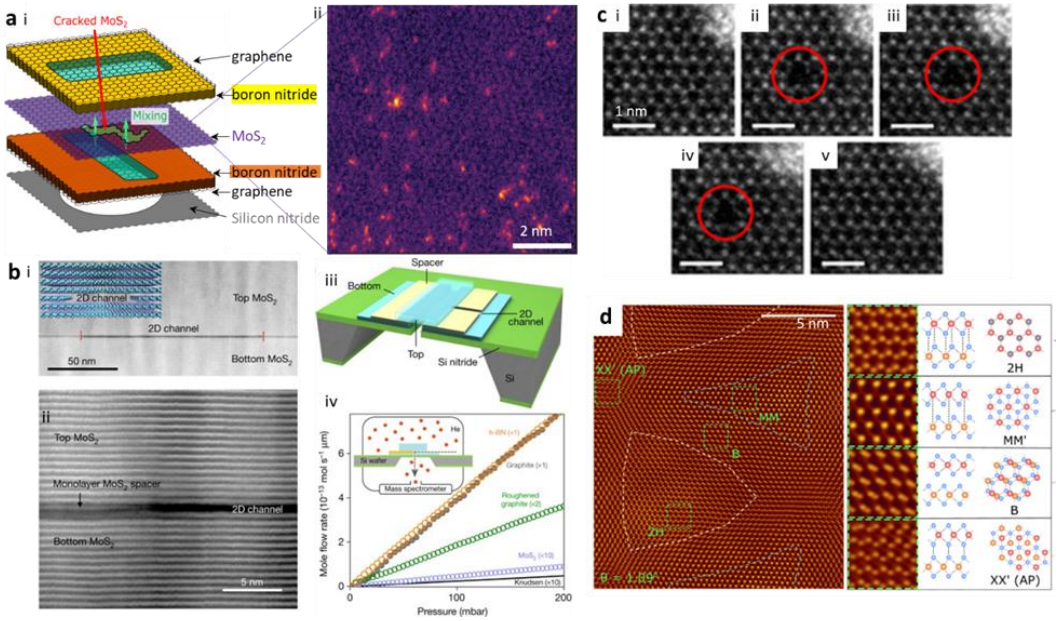

Figure 1 (a) i) 2D heterostructure TEM mixing cell platform [1] (ii) TEM movie imaging dynamics of Pt atoms in liquid [2]. (b) (i-iv) 2D nanochannels and their flow behaviour [3], (c) i-v) Formation and healing of single Se vacancies in InSe [4]. (d) TEM imaging of local lattice reconstruction in a twisted WS_2-WS_2 bilayer [5].

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Carbon Nanotubes for Cancer Research and Diagnosis

Daniel A. Heller
Memorial Sloan Kettering Cancer Center
New York, NY 10065, USA
hellerd@mskcc.org

Additional Authors: Mijin Kim, Zvi Yaari, Yoona Yang, Chen Chen, Merav Antman-Passig, Ewelina Randall, Ron Feiner, Prakrit Jena, Peng Wang, YuHuang Wang, Anand Jagota, Ming Zheng

New technologies are needed for the early detection of cancer and the identification of therapeutic vulnerabilities in cancers. Our laboratory develops optical nanosensor technologies using carbon nanotubes, including sensors that identify disease fingerprints in serum, diagnostic implants to facilitate longitudinal detection of cancer biomarkers, and assays for cancer drug development. These methods employ the photoluminescence of single-walled carbon nanotube (SWCNTs) and covalent sp3 quantum well defects on SWCNTs, aka organic color centers (OCCs), that introduce new chemical sensitivities. To develop new detection technologies using OCC-modified SWCNTs, we introduced new supramolecular functionalization methods, as well as new types of optical instrumentation to detect changes in near-infrared emission within biological and clinical samples. We harnessed OCC-modified SWCNTs for the detection of metabolic changes in live cells and tissues, disease biomarkers in situ via implants, and overall disease states, aided by machine learning processes.

Developing Quantum Photon Sources from Low-dimensional Semiconductor Materials

Xuedan Ma
Center for Nanoscale Materials
Argonne National Laboratory

Optical photons are ubiquitous in quantum communication and storage applications due to their long coherence times and ease to travel over long distances. On-demand quantum photon sources that may emitter single photons as quantum information carriers are especially sought after for quantum-related applications. In this talk, I will present our recent effort in the development of solid-state quantum photon sources based on low-dimensional semiconductor materials. By molecular doping[1-3] and wavefunction engineering,[4-6] we have demonstrated versatile material platforms that allow efficient single photon generation and modulation. Approaches for achieving facile light-matter interaction by coupling the quantum photon sources to photonic structures will also be discussed.

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Broad Applications using Graphene Quantum Dots with Discrete Bandgap

Seokwoo Jeon

Department of Materials Science and Engineering, Advanced Battery Center, KI for the Nano Century, KAIST, 291 Daehak-ro, Yuseong Gu, Daejeon 34141, Korea

Email: jeon39@kaist.ac.kr

Graphene is a 2D material with atomic thickness and possesses unusual thermal, electrical, optical, and mechanical properties. Even though graphene has no discrete bandgap, smaller graphene below ~10 nm in its diameter starts to show luminescence and phosphorescence. Our group has focused on the synthesis of non-oxidized graphene flakes (NOGF) from graphite through intercalation. With the advantage of the methods generally excluding, or controlling, the oxidation of 2D materials, one notable application of controlled oxidation of graphene is graphene quantum dots (GQDs), simply making graphene smaller typically under 10 nm. GQD could be a new class of optical material with low cost and superior photo- and chemical-stability. The origin of intrinsic emission (~ 400 nm) of graphene is the isolated small sp2 carbon hexagons within a GQD, known as subdomains. Experimental evidences supported with calculation of the formation energy of subdomains and bandgap will give a guideline to improve emission properties. Further control in GQD diameter below 5 nm is strongly coupled with the color purity of GQD and Quantum Yield up to several 10s of percent. With those understanding the first demonstration of GQD light-emitting diodes (GQD-LEDs) with 1,000 cd/m2, alternating current powder elctroluminescence (ACPEL) device with good stability promise the optical applications of GQDs. Further study on the coupling of GQD with organic phosphor or photocatalytic oxides will extend the usefulness of GQD to untapped applications such as photovoltaics, water purification, sun cream, and OLED booster.

Degradation of Carbon Nanotubes in the Presence of Bacterial Enzymes

Katsutoshi Hori[1,2], Seira Takahashi[1], Fumiko Taguchi[1], Junichi Kanie[2], Mitsuo Ueno[3], Mitsugu Uejima[3], Masafumi Ata[3]

[1] Department of Biomolecular Engineering, Nagoya University, [2]Friend Microbe Inc., [3]CNT Laboratory, Zeon Corporation
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
khori@chembio.nagoya-u.ac.jp

The enzymatic degradation of carbon nanotubes (CNTs) by several enzymes has been reported [1-5]. However, because organisms that possess these enzymes have limited habitats and distribution areas, it is unclear whether CNTs can be degraded in the general environment. The investigation of CNTs degradation by enzymes derived from bacteria, which inhabit a wide range of environments and have diverse metabolic systems, is inevitable for predicting the environmental fate of CNTs. In this study, the degradation of oxidized (carboxylated) single-walled CNTs (O-SWCNTs) by mt2DyP, a dye-decolorizing peroxidase of *Pseudomonas putida* mt-2, a common soil bacterium [6], was investigated. Suspensions of O-SWCNTs gradually became transparent and their optical absorbance decreased during 30 d of incubation in the presence of mt2DyP produced by a recombinant *Brevibacillus choshinensis* strain and its substrate, H_2O_2. The degradation was enhanced by higher H_2O_2 concentrations. The measurement of Raman spectra revealed the complete degradation of O-SWCNTs after 30 d of incubation with 100 mM H_2O_2. However, surprisingly, this heme enzyme was inactivated within 60 min of the incubation with O-SWCNTs, which suggested that the degradation of O-SWCNTs was not catalyzed by the enzyme. The inactivation of mt2DyP was accompanied by the release of iron, which suggested that the degradation of the O-SWCNTs was owing to the Fenton reaction caused by the iron released from mt2DyP and the supplied H_2O_2. A chelating agent, diethylenetriaminepentaacetic acid, significantly inhibited the O-SWCNTs degradation, proving the degradation by the Fenton reaction. These phenomena were also observed with another heme enzyme, Cytochrome P450. These results are important for predicting the fate of CNTs in a wide range of environments, as heme enzymes are secreted by many bacteria in the environment.

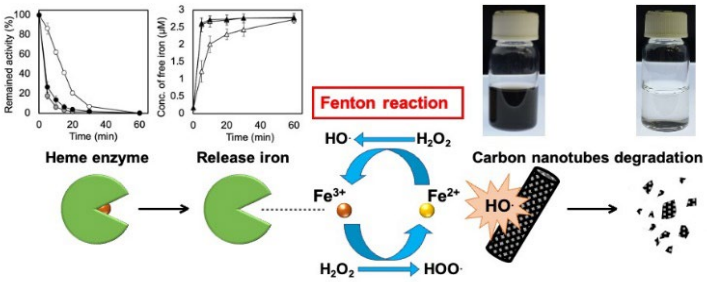

Fig. 1 Degradation of CNT by bacterial heme enzymes

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Theoretical Insight into New Strategies of Carbon Nanotube Functionalization

Sergei Tretiak
Theoretical Division and Center for Integrated Nanotechnologies,
Los Alamos National Laboratory, Los Alamos NM, 87545
E-mail: serg@lanl.gov

An intentional introduction of quantum defects to the carbon nanotube surface leads to unique photoluminescence properties that may be useful for a wide range of optoelectronic, sensing, imaging and quantum communication applications. Quantum-chemical simulations help to rationalize spectroscopic observation and fine tune synthetic strategies. I will overview photosynthetic control of chemical binding configurations of quantum defects through the spin multiplicity of photoexcited intermediates. Here photoexcited aromatics react with SWCNT sidewalls to undergo a singlet-state pathway in the presence of dissolved oxygen, leading to ortho binding configurations of the aryl group on the nanotube. In contrast, the oxygen-free photoreaction activates previously inaccessible para configurations through a triplet-state mechanism. To understand the atomistic mechanism of these photo-activated reactions and their dependence on spin multiplicity, we have modeled the reaction with and without triplet quenching using density functional theory. Computed reaction pathways demonstrate selectivity and dependence of outcomes of the photo-activated reaction on the presence or absence of triplet quenching, corresponding to presence or absence of oxygen, respectively. Such spin-selective photochemistry diversifies SWCNT emission tunability by controlling the morphology of the emitting sites.

Control of Electronic Band Profiles by Depletion Layer Engineering in Core-Shell Metal Oxide Nanocrystals

Nicola Curreli[1], Ilka Kriegel[1]

[1] *Functional Nanosystems, Italian Institute of Technology*

Via Morego, 30, 16163 Genoa, Italy

nicola.curreli@iit.it; ilka.kriegel@iit.it

Optical and electronic properties of metal oxide nanocrystals (MO NCs) strongly depend on the presence of depletion layers derived from the presence of surface states. In addition, MO NCs exhibit a localized surface plasmon resonance (LSPR), offering tunable features enabled by doping, both via electrochemical or photochemical charging. Dynamic control over the LSPR makes MO NCs promising in optoelectronics and storage devices. By manipulating the NCs depletion layer, it is possible to control their electronic properties. However, the mechanism behind this phenomenon is very complex, and not yet fully understood. In particular, the tuning of several parameters, including the material under consideration, the size of the NCs, and the presence of multiple core-shell systems, enable the depletion layer engineering. To do this, it is possible to calculate the band and carrier density profiles for NCs with different features. In this work, a new framework has been introduced that can predict the behavior and physics under the MO NC photodoping process, revealing that the charging mechanism is unexpectedly based on the electronic rearrangement of the energy bands. Numerical simulations were experimentally supported by studying the case of a core-shell structure of Sn:In_2O_3/In_2O_3 NCs, by tuning the thickness of the shell, as well as post-synthetically, both by photodoping and reversible chemical reactions. The engineering of the depletion layer and the consequent manipulation of the electronic structure allows to significantly increase the sensitivity of LSPR and to target specific properties in MO NCs. The fine-tuning of the NCs band structure has enabled an improvement in charge storage capacity, which represents a step towards fully light-driven energy storage devices.

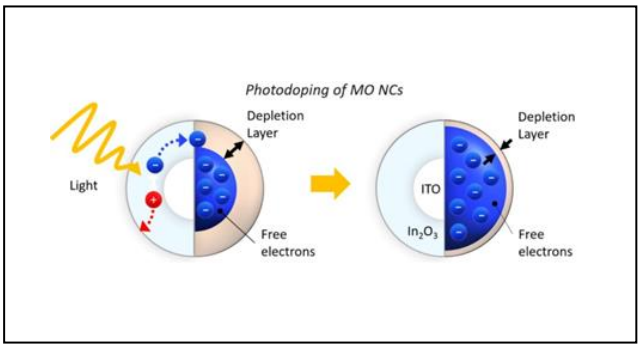

Fig 1. Illustration of a core-shell ITO-In_2O_3 nanocrystal (NC) before (left) and after (right) the photodoping process driven by light absorption. The left side of each sphere represents the physical structure of the NC, with the ITO core and In_2O_3 shell depicted with different colours (white and light blue, respectively). The right side represents a simplified picture of the NC's electronic structure.

The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

Parallel Symposia Program & Abstract

2D Material

Parallel Symposia **2D MATERIAL @ Auditorium**

Tuesday, JUNE 21st, 2022

		Chair: Vincent Tung (KAUST)
14:30-15:00	P-2D-I1	**Lain-Jong Li** (The University of Hong Kong, Hong Kong) *Towards high-performance transistors based on 2D transition metal dichalcogenide monolayers*
15:00-15:30	P-2D-I2	**Kibum Kang** (KAIST, Korea) *Beyond Binary 2D Metal-Chalcogenides: 2D Ternary Metal Chalcogenides and 2D Oxides*
15:30-15:40	Short break	
		Chair: Kibum Kang (KAIST, Korea)
15:40-16:10	P-2D-I3	**Jong-Hyun Ahn** (Yonsei University, Korea) *Direct growth of MoS2 on III-V semiconductor for optoelectronics applications*
16:10-16:40	P-2D-I4	**Jiaxing Huang** (Northwestern University, USA) Seeing 2D Materials with Fluorescence quenching microscopy: An Update
16:40-17:00	P-2D-C1	**Pilkyung Moon** (New York University Shanghai, China) *Resonant interaction in chiral Eshelby-twisted van der Waals atomic layers*

Thursday, JUNE 23rd, 2022

		Chair: Lain-Jong Li (The University of Hong Kong)
14:30-15:00	P-2D-I5	**Xinran Wang** (Nanjing University, China) *Recent advances in 2D semiconductor growth, high-performance devices, and heterogeneous integration*
15:00-15:30	P-2D-I6	**Hyeon Suk Shin** (UNIST) *Growth of Monolayer and Few-Layer Hexagonal Boron Nitride by Chemical Vapor Deposition*
15:30-15:40	Short break	
		Chair: Kikang Kim (Sungkyunkwan University)
15:40-16:10	P-2D-I7	**Vincent Tung** (KAUST, Kingdom of Saudi Arabia) *Wafer-scale synthesis of 2D semiconductors on structured and reusable substrate*
16:10-16:30	P-2D-C2	**Sayyed Sajjadi** (EPFL, Switzerland) *Photoluminescence brightening of single-walled carbon nanotubes through conjugation with Graphene quantum dots*
16:30-16:50	P-2D-C3	**Young Seo Jeon** (Sungkyunkwan University, Korea) *Wafer-scale 2D MoSe2 phototransistor array via liquid-precursor-assisted chemical vapor deposition*

Towards high-performance transistors based on 2D transition metal dichalcogenide monolayers

Lain-Jong Li
The University of Hong Kong
Department of Mechanical Engineering, Pokfulam Road, Hong Kong
lanceli1@hku.hk

Two-dimensional (2D) semiconducting monolayers such as transition metal dichalcogenides (TMDs) are promising channel materials to extend Moore's Law in advanced electronics. To make high-performance devices based on 2D semiconductors such as WS_2 monolayers, many issues need to be resolved. In this presentation, I we like to discuss several advancements we and collaborators have achieved recently. (1) We discover that hydroxide vapor phase epitaxy enables the growth of WS2 monolayers with a significantly lower density of structural defects, which make the electron mobility peaked at ~ 200 cm^2/Vs. (2) Ultrahigh-k dielectrics can be applied onto short-channel (<30 nm) 2D monolayer transistors to greatly lower the subthreshold swing (down to 70 mV dec^{-1}) with an ON/OFF current ratio up to 10^7. (3) Semimetal is a feasible n-type contact metal to TMD monolayers.

Beyond Binary 2D Metal-Chalcogenides: 2D Ternary Metal Chalcogenides and 2D Oxides

Kibum Kang[1]

[1]*Department of Materials Science and Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*

The 2D layered materials are the potential components in next-generation semiconductor devices and quantum devices. At the beginning of 2D semiconducting material research, the binary metal chalcogenides have been popularly studied, such as MoS_2, WS_2, $MoSe_2$, WSe_2, etc. Currently, it has been found that approximately 100 types of 2D materials can be grown. However, according to recent high-throughput calculations, more than 1,000 types of two-dimensional materials have yet to be revealed. Here, we will introduce the recent advances for the growth of new 2D materials beyond binary metal chalcogenides, including 2D ternary metal chalcogenides, 2D oxides, and 2D metastable materials. For exploring the new 2D materials, we used the gas-phase growth, especially metal-organic chemical vapor deposition, to take advantage of precursor controllability. Furthermore, we investigated the electrical, optical, and mechanical functionality of the newly discovered materials. Through the 2D material discovery effort, we will be able to contribute to generate a library of 2D materials and improve the performance and the functionality of 2D material devices.

Direct growth of MoS_2 on III-V semiconductor for optoelectronics applications

Jong-Hyun Ahn

School of Electrical and Electronic Engineering, Yonsei University

50 Yonsei-ro, Seodaemun-gu, Seoul, Republic of Korea

ahnj@yonsei.ac.kr

Large-scale growth of transition metal chalcogenides and their subsequent integration with III-V compound semiconductors is one of the major obstacles for two-dimensional materials implementation in optoelectronics applications. In this talk, I present a direct growth of transition metal chalcogenides on III-V compound semiconductor that is compatible with a batch microfabrication process. We show how a thin film of molybdenum disulfide (MoS_2) can be directly synthesized on a gallium-nitride-based epitaxial wafer to form a thin film transistor array. Subsequently, the MoS_2 thin film transistor was monolithically integrated with micro-light-emitting-diode (micro-LED) devices to produce an active matrix micro-LED display. This strategy represents a promising route to attain heterogeneous integration, which is essential for high-performance optoelectronic systems that can incorporate the established semiconductor technology and emerging two-dimensional materials.

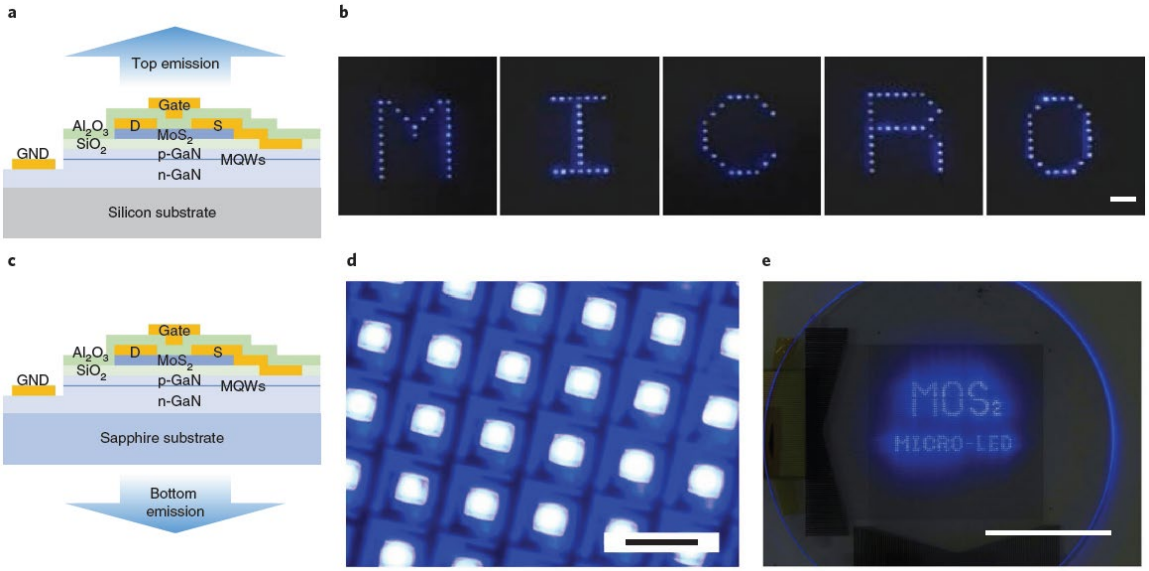

Fig 1. a) Schematic of integrated device fabricated on silicon substrate with top emission. b) Optical images of the active matrix micro-LED display operated using an external driving circuit displaying characters M, I, C, R and O. Scale bar, 2 mm. c) Schematic of integrated device fabricated on sapphire substrate with bottom emission. d) Photograph of bottom emission micro-LED display on a 2 inch sapphire substrate with ~100% emission area ratio. Scale bar, 200 μm. e) Optical image of bottom emission display operated using an external driving circuit displaying characters. Scale bar, 2 cm.

Seeing 2D Materials with Fluorescence quenching microscopy: An Update

Zhizhi Kong[1,2] and Jiaxing Huang[2,3*]
1. *University of California, Berkeley, CA USA*
2. *Northwestern University, IL USA*
3. *Westlake University, Hangzhou, China*

Corresponding Address
Jiaxing-huang@westlake.edu.cn

Fluorescence quenching microscopy (FQM) was initially developed for high throughput imaging of graphene based sheets on arbitrary substrates under a common fluorescence microscopy. It takes advantages of the long range, energy transfer-based fluorescence quenching effect of graphene-based materials, and can obtain images with high contrast and high layer resolution comparable to those of scanning electron microscopy (SEM) and atomic force microscopy (AFM). FQM was later applied to image other strongly quenching sheets such as transitional metal dichalcogenides.

The high-contrast optical imaging of nearly transparent 2D materials such as clays and some oxides sheets has been an outstanding challenge; yet it is a critical research capability needed in the synthesis and processing of these materials, which have shown promise in a number of applications including barrier coatings, membranes, and composites. Using delaminated silicate clay and titania sheets as model system, here we show that these weakly quenching, nearly transparent 2D sheets can also be readily imaged by FQM based on a new mechanism with SEM and AFM level of contrast and layer resolutions. When different 2D materials are co-deposited, FQM not only differentiates them readily based on their quenching capabilities, but also can resolve their vertical stacking sequence based on the contrast of their overlapped areas.

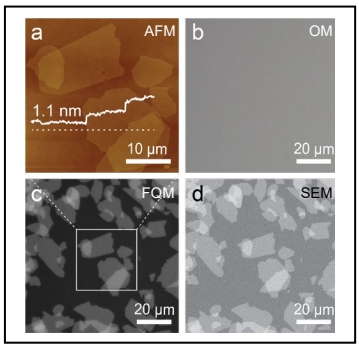

Fig 1. FQM can image 2D sheets (the example shown here is nearly transparent clay sheets) with high contrast and layer resolution comparable to AFM and SEM

Resonant interaction in chiral Eshelby-twisted van der Waals atomic layers

Pilkyung Moon [a,b,c,d]

[a] *Arts and Sciences, New York University Shanghai, Shanghai 200122, China*
[b] *NYU-ECNU Institute of Physics at NYU Shanghai, Shanghai 200062, China*
[c] *Department of Physics, New York University, New York 10003, USA*
[d] *Center for Quantum and Topological Systems, New York University Abu Dhabi, UAE*
pilkyung.moon@nyu.edu

We study the electronic structures of chiral, Eshelby-twisted van der Waals atomic layers with a particular focus on a chiral twisted graphite (CTG), a graphene stack with a constant twist angle θ between successive layers [1]. We show that each CTG can host infinitely many quasicrystalline resonant states which arise from the interaction between the degenerate monolayer states of the constituent layers. Each resonant state has a screw rotational symmetry, and may have a smaller reduced Brillouin zone than other non-resonant states in the same structure. And each CTG can have the quasicrystalline states with up to four different screw symmetries. We derive the energies and wave functions of the quasicrystalline states in a universal form of a one-dimensional chain regardless of θ, which is analogous to that of graphene quasicrystals [2], and show that these states exhibit a clear optical selection rule for circularly polarized light [1]. Finally, we discuss the uniqueness and existence of the exact center of the lattice and the self-similarity of the wave amplitudes of the resonant states [1, 3].

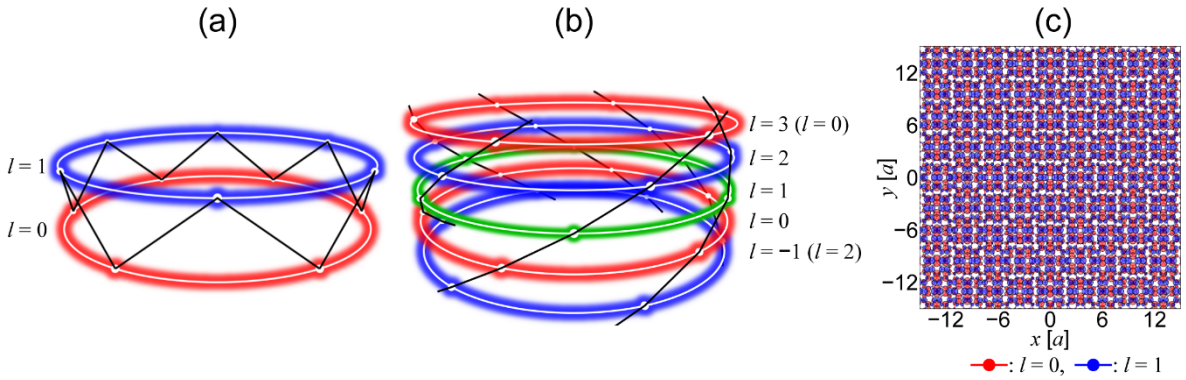

Fig. 1 (a) An illustration of the quasicrystalline resonant interaction in graphene quasicrystals. (b) A plot similar to (a) for a CTG with a 12-fold screw rotational symmetry. (c) Spatial distribution of the quasicrystalline wave functions with a 4-fold screw rotational symmetry in a CTG with a 12-fold screw rotational symmetry.

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Recent advances in 2D semiconductor growth, high-performance devices and heterogeneous integration

Xinran Wang
Nanjing University
xrwang@nju.edu.cn

2D transition-metal dichalcogenide semiconductors are promising candidates in future electronics due to unmatched device performance at atomic limit and low-temperature heterogeneous integration. In this talk, I will present our recent advances in this area. The main topics include wafer-scale single-crystal epitaxial growth, uniform bi-layer material growth, dielectric integration and Ohmic contact technology, and heterogeneous integration for advanced electronics and optoelectronics applications.

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Growth of Monolayer and Few-Layer Hexagonal Boron Nitride by Chemical Vapor Deposition

Hyeon Suk Shin
Departoment of Chemistry, UNIST, Ulsan 44919, Korea

Large-scale growth of high-quality hexagonal boron nitride has been a challenge in the field of two-dimensional materials. In this talk, I demonstrate the growth of highly crystalline, monolayer h-BN on Pt foil and wafer-scale few-layer hBN on sapphire substrate by a low-pressure chemical vapor deposition method. The UV–visible absorption spectra of the monolayer and few-layer h-BN suggested an optical band gap of around 6 eV, while high-resolution transmission electron microscopy images of the same showed the presence of distinct hexagonal arrays of B and N atoms and AA′ stacking order for few-layer hBN. Furthermore, I demonstrate recent results on the epitaxial growth of wafer-scale single-crystal few-layer hBN by a chemical vapor deposition method. Uniformly aligned few-layer hBN islands are found to grow on a 2 cm × 5 cm single-crystal Ni (111) at early stage of growth and finally to coalesce into a single-crystal film.

Wafer-scale synthesis of 2D semiconductors on structured and reusable substrate

Vincent Tung

King Abdullah University of Science and Technology (KAUST)

[1]Physical Science and Engineering Division, Material Science and Engineering Program, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Kingdom of Saudi Arabia

vincent.tung@kaust.edu.sa

Two-dimensional (2D) transition metal dichalcogenide (TMD) monolayers have been c onsidered promising for future transistor device downscaling. The growth of high-qualit y and single-crystal TMD monolayers are yet to be developed for electronic applicatio ns. Here we show that step-edge epitaxy growth enables the controllable and scalable growth of single-crystal 2D monolayers. In this talk, I will present our recent findings in a ledge-directed epitaxy (LDE) of dense arrays of continuous, self-aligned, monolayer and single-crystalline MoS_2 nanoribbons and films on β-gallium (III) oxide (β-Ga_2O_3) (100) substrates. LDE MoS_2 nanoribbons have spatial uniformity over a long-range and transport characteristics on par with those seen in exfoliated benchmarks. Prototype MoS_2 nanoribbon-based field-effect transistors exhibit high on/off ratios of 10^8 and a peak room temperature electron mobility of 109 $cm^2V^{-1}s^{-1}$. The MoS_2 nanoribbons can be readily transferred to arbitrary substrates while the underlying β-Ga_2O_3 can be re-used after mechanical exfoliation. We further demonstrate LDE as a versatile epitaxy platform for the growth of p-type WSe_2 nanoribbons and lateral heterostructures made of p-WSe_2 and n-MoS_2 nanoribbons for futuri stic electronics applications.

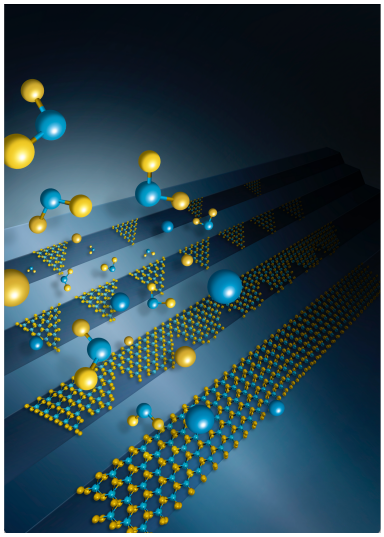

Fig 1. Epitaxy growth of continuously single-crystal 2D transitional metal dichalcogenides (TMD) on structured and reusable metal oxide substrates.

Photoluminescence brightening of single-walled carbon nanotubes through conjugation with Graphene quantum dots

Sayyed Hashem Sajjadi, Shang-Jung Wu, Melania Reggente, Niloufar Sharif, Ardemis A. Boghossiana*

École Polytechnique Fédérale de Lausanne (EPFL), CH-1015, Lausanne, Switzerland
Corresponding Address
ardemis.boghossian@epfl.ch

Spanning the tissue transparency window, the near-infrared (NIR) SWCNT photoluminescence (PL) can optically penetrate biological tissue for deep-tissue imaging and optical sensing. SWCNTs are often functionalized with single stranded DNA (ssDNA) to yield sensors that are biocompatible, responsive, and selective. However, the low brightness of these ssDNA-wrapped sensors restricts the depth at which such sensors can be implanted in the tissue. In this work, we demonstrate the PL enhancement of ssDNA-wrapped SWCNTs through the incorporation of biocompatible graphene quantum dots (GQDs). Two kind of GQDs, pristine (PGQDs) and nitrogen-doped (NGQDs), were fabricated and characterized. Thermodynamically, both GQDs were shown to significantly increase the fluorescence efficiency of ssDNA-SWCNTs with the same degree of PL enhancement after 3 h. A correlation between the diameter of the SWCNTs and the PL enhancement factor was approved, the larger the SWCNT diameter, the higher the PL increase upon addition of GQDs. For example, a 30-fold enhancement was achieved for (8,6) chirality while it was only 2-fold for the (6,5) chirality. Our experiments showed that the addition of GQDs leads to an increase in the surface coverage of SWCNTs suspended by ssDNA, limiting water molecules access to the nanotube surface and thus increasing the fluorescence efficiency. Kinetically, NGQDs brightened SWCNTs much faster than PGQDs. The PL intensity reached a plateau in 2 min following addition of NGQDs while it was still increasing even after 1 h upon addition of PGQDs. We show that NGQDs can act as reducing agent to decrease the dissolved oxygen, which quench the SWCNTs PL. This advancement provides promising tools for engineering the brightness of NIR sensors for biomedical applications such as single-molecule imaging of individual SWCNTs using NIR confocal microscopy and deep tissue sensing.

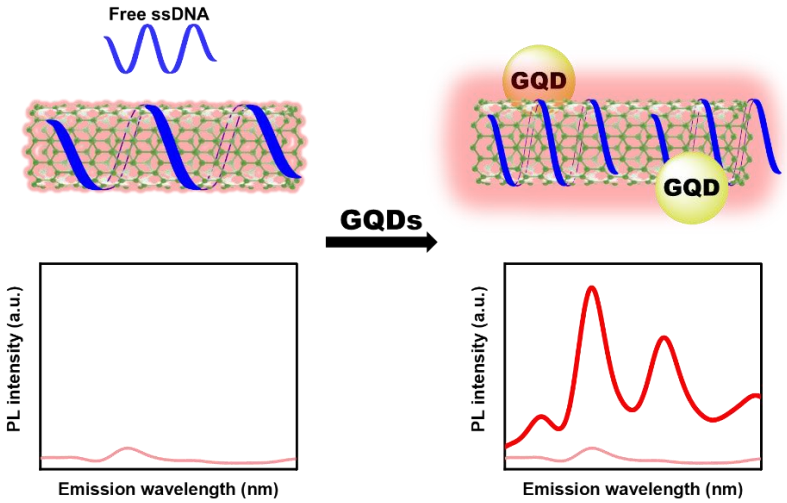

Fig 1. Cartoon presentation of PL brightening of ssDNA-SWCNTs by adding GQDs.

Wafer-scale 2D $MoSe_2$ phototransistor array via liquid-precursor-assisted chemical vapor deposition

Youngseo Jeon

School of Advanced Materials Science and Engineering, Sungkyunkwan University (SKKU), Suwon 16419, Republic of Korea

vip3929@skku.edu

Two-dimensional (2D) nanomaterials especially monolayer transition metal dichalcogenides (TMDs) have shown promise for realizing miniaturized photodetectors because they are atomically thin and exhibit unique electronic and optical properties compared to bulk semiconductors. For a good photoelectronic device, centimeter-scale and continuous TMDs with spatial homogeneity are needed. The chemical vapor deposition (CVD) using liquid-phase precursors have been developed for that large scale, homogeneous film. However, as-synthesized film through this method is usually composed of chalcogen-deficient, nanosized grains and thus exhibits not as good optoelectronics properties.

Here we demonstrate that a liquid-phase CVD process with a growth promoter can produce high-quality monolayer TMD films for a wafer-scale photodetector array. By mixing potassium iodide growth promoter to the ammonium transition metal oxide precursor solution, we could reduce the energy barrier for chalcogenization of the precursor film and enhance the lateral growth of TMDs. As a representative TMD material, molybdenum diselenide ($MoSe_2$) was synthesized via the promoter-assisted growth strategy, which yielded a continuous monolayer film with high crystallinity. The use of growth promoter significantly enhanced the electronic and optical properties of the MoSe2 and hence photoresponsivity of the resulting photodetector array was much higher compared to the device formed only with the precursor.

We will discuss about significantly enhanced electronic and optical properties of synthesized MoSe2 with KI promoter. The high photoresponsivities of the $MoSe_2$ monolayer with promoter under R(785-nm), G(520-nm), and B(450-nm) wavelengths will be shown and the spatial uniformity of the photoresponse will be shown through the photocurrent mapping.

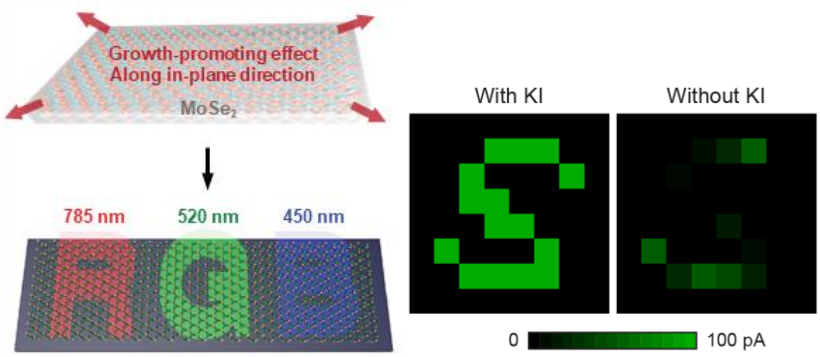

Fig 1. Schematics of growth of large area $MoSe_2$ monolayer and photoresponse, photocurrent mapping of an 8x8 photodetector array under 520-nm light illumination

Friday, JUNE 24th, 2022

		Chair: Maeng Je Seong (Chung-Ang University)
13:15-13:45	P-2D-I8	**Clément FAUGERAS** (EMFL, France) *High Pressure tuning of magnon-polarons in the layered antiferromagnet FePS3*
13:45-14:15	P-2D-I9	**Christoph STAMPFER** (RWTH Aachen University, Germany) *Spin-valley coupling in graphene quantum dots*
14:15-14:25	Short break	
		Chair: Ksenia Bets (Rice university)
14:25-14:55	P-2D-I10	**Guillaume CASSABOIS (**Montpellier University, France) *Efficient light-matter interaction in hexagonal boron nitride*
14:55-15:15	P-2D-C4	**Naoto Nakatsuji** (Osaka University, Japan) *The moiré distortion effect on the flat band of the magic-angle twisted bilayer graphene*
15:15-15:35	P-2D-C5	**Mohammed Alamri** (University of Umm Al-Qura, Saudi) *Ultraviolet-activation improved H2 gas sensing using ALD Pt decorated 3D carbon nanotube/graphene nanostructures*

High Pressure tuning of magnon-polarons in the layered antiferromagnet $FePS_3$

A. Pawbake[1], T. Pelini[1], A. Delhomme[1], D. Romanin[2], D. Vaclavkova[1], G. Martinez[1] M. Calandra[3], M.-A. Measson[4], M. Veis[5], M. Potemski[1], M. Orlita[1], C. Faugeras[1]

[1]LNCMI-CNRS, EMFL, Grenoble, France
[2]Sorbonne University, INSP, CNRS, Paris, France
[3]Universita di Trento, Povo, Italy
[4]Institut Néel, CNRS, Grenoble
[5]Charles University, Prague, Czech Republic
clement.faugeras@lncmi.cnrs.fr

Magnetic layered materials have recently stimulated a lot of efforts to understand their magnetic properties and to use them in functional devices based on the propagation of spin waves or on proximity effects. $FePS_3$ is an antiferromagnetic material hosting magnons at an unusually high energy of 120 cm^{-1}, comparable to that of phonons. It was recently shown that the magnetoelastic interaction in this material leads to the formation of magnon polarons [1,2] when magnetic field is used to tune one the two magnon branches in resonance with phonons.

In this contribution, we report on low temperature Raman scattering experiments performed on bulk $FePS_3$ under hydrostatic pressure up to 8 GPa. In this layered compound, applying hydrostatic pressure modifies the phonon spectrum without affecting the magnon energy. It is then possible to tune phonon excitations through the magnon and to generate magnon-polarons involving the doubly degenerate antiferromagnetic magnon. The magnon-phonon resonance is achieved close to P=4 GPa, for which a pronounced modification of the Raman scattering response is observed. With an external magnetic field up to B=30 T, it is possible to identify clearly the different contributions to the Raman scattering spectrum, and also to generate magnon-polarons involving the high energy magnon branch. $FePS_3$ under pressure appears as a platform to generate magnon-polarons with arbitrary phonon-magnon energy detuning.

[1] S. Liu et al., Phys. Rev. Lett. **127**, 097401, (2021)

[2] D. Vaclavkova et al., Phys. Rev. B **104**, 134437, (2021)

Spin-valley coupling in graphene quantum dots

Christoph Stampfer [a, b]
[a] *JARA-FIT and 2nd Institute of Physics, RWTH Aachen University, 52074 Aachen, Germany*
[b] *Peter Grünberg Institute (PGI-9), Forschungszentrum Jülich, 52425 Jülich, Germany, EU*
stampfer@physik.rwth-aachen.de

Graphene and bilayer graphene (BLG) are attractive platforms for quantum circuits with potential applications in the area quantum information. This has motivated substantial efforts in studying quantum dot devices based on graphene and bilayer graphene. A major challenge in this context is the missing band-gap in graphene, which does not allow to confine electrons by means of electrostatics making ultra-clean displacement field-gapped BLG particularly interesting.

Here we present gate-controlled single and double quantum dots in electrostatically gaped BLG [1,2]. We show a remarkable degree of control of our devices, which allow realizing electron-hole and electron-electron double quantum dot systems with single-electron occupation (see Fig. 1). In both, the single and double quantum dot devices, we reach the very few electron/hole regime, we are able to extract excited state energies and investigate their evolution in a parallel and perpendicular magnetic field. Finally, we will show data on ultra-clean BLG quantum dots allowing investigating the spin-valley coupling in bilayer graphene [2]. Our work paves the way for the implementation of spin and valley-qubits in graphene.

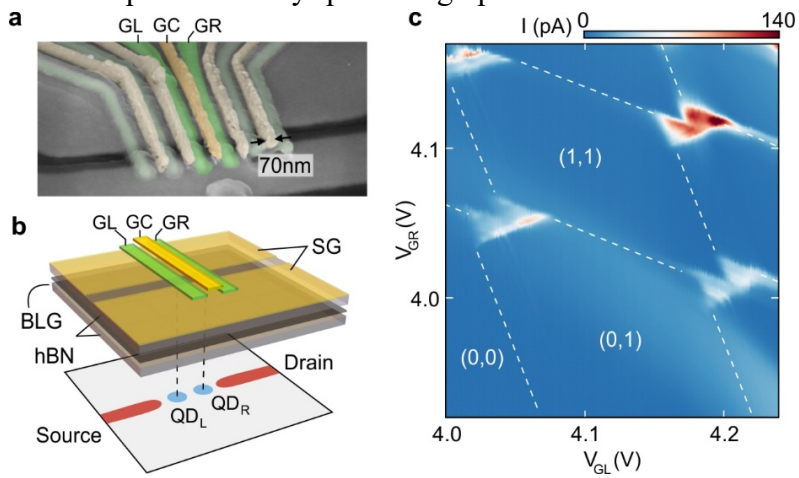

Fig. 1 (a) Scanning electron microscopy image of a BLG dot sample. (b) Schematics of the sample. (c) Charge stability diagram of the double quantum dot. Taken from Ref. [2].

References

[1] S. Möller, L. Banszerus, A. Knothe, C. Steiner, E. Icking, S. Trellenkamp, F. Lentz, K. Watanabe, T. Taniguchi, L. Glazman, V. Fal'ko, C. Volk, and C. Stampfer, Phys. Rev. Lett. 127, 256802 (2021)
[2] L. Banszerus, S. Möller, C. Steiner, E. Icking, S. Trellenkamp, F. Lentz, K. Watanabe, T. Taniguchi, C. Volk, and C. Stampfer, Nature Communications 12, 5250 (2021)

Efficient light-matter interaction in hexagonal boron nitride

Guillaume CASSABOIS[1]

[1]*Laboratoire Charles Coulomb, CNRS, Montpellier University, 34095 Montpellier, France*

Hexagonal boron nitride (hBN) is an ultrawide bandgap semiconductor with a large range of basic applications relying on its low dielectric constant, high thermal conductivity, and chemical inertness. The growth of high-quality crystals in 2004 has revealed that hBN is also a promising material for light-emitting devices in the deep ultraviolet domain, as illustrated by the demonstration of lasing at 215 nm by accelerated electron excitation [1], and also the operation of field emitter display-type devices in the deep ultraviolet [2]. With a honeycomb structure similar to graphene, bulk hBN has gained tremendous attention as an exceptional substrate for graphene with an atomically smooth surface, and more generally, as a fundamental building block of Van der Waals heterostructures [3].

I will discuss here our recent measurements characterizing the light-matter interaction in hBN. In bulk hBN, high-resolution reflectivity experiments in high-quality crystals have allowed to resolve the respective contributions of indirect and direct optical transitions and quantify the strength of the light-matter interaction, reaching record values in hBN [4]. In monolayer hBN epitaxially grown on graphite, the radiative broadening was estimated by systematic studies as a function of the hBN surface coverage. Values as high as ~25 meV are found for the radiative linewidth. This work highlights the outstanding light-matter interaction in both 3D and 2D forms of hBN.

References:

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[2] K. Watanabe, T. Taniguchi, T. Niiyama, K. Miya, and M. Taniguchi, Nature Photon. **3**, 591 (2009).
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The moiré distortion effect on the flat band of the magic-angle twisted bilayer graphene

Naoto Nakatsuji and Mikito Koshino
Dept. of Phys. Osaka Univ.
Toyonaka, Osaka, Japan
n.nakatsuji@qp.phys.sci.osaka-u.ac.jp

We theoretically investigated the effect of uniform / non-uniform distortion on the energy bands in the magic-angle twisted bilayer graphene (MATBG). The MATBG has a flat band around the charge neutral point, and it is usually described by the moiré band theory, which is based on a regular periodicity of the moiré superlattice. On the other hand, it is also known that the moiré pattern of the actual TBG samples is not perfectly regular due to the local distortion, but exhibits a random super-moiré pattern with a local variance of the twist angle [1,2].

Here, we study the effect of such a moiré pattern distortion on the flat band of TBG [Fig. 1(a)]. We find that the random distortion splits the two degenerate flat bands into two separate portions in the energy axis [Fig. 1(b)], rather than simply broadening the band. We find that the split of the flat bands is mainly caused by the strain-induced vector potential in the Dirac Hamiltonian, and the splitting width in the local density of states highly correlates with the local value of the vector potential. The exclusive dependence on the strain-induced vector potential is explained by the pseudo landau level picture for the magic-angle flat band [3].

[1] L. Huder, et al., Phys. Rev. Lett. **120**, 156405 (2018).
[2] A. Uri., et al. Nature **581,** 47–52 (2020).
[3] J. Liu, et al., Phys. Rev. B **99**, 155415 (2019).

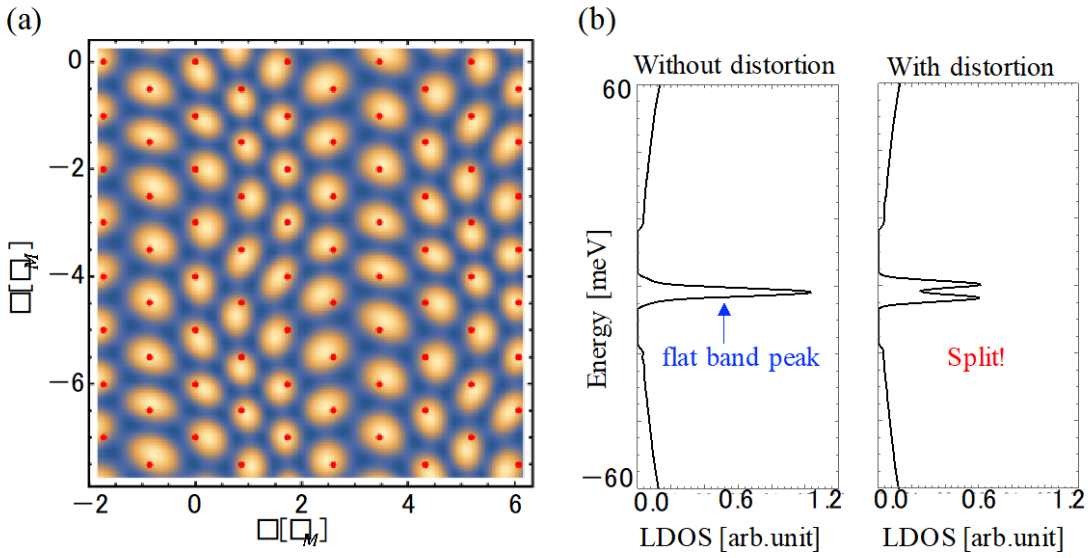

Fig. 1. Moiré lattice structure of TBG at $\theta = 1.05$ degree with a non-uniform distortion. The bright and dark regions represent AA and AB/BA stacking points respectively. The red points represent AA stacking points of a regular TBG. (b) The local density of state at AA stacking point without distortion (left) and with distortion (right).

Ultraviolet-activation improved H_2 gas sensing using ALD Pt decorated 3D carbon nanotube/graphene nanostructures

Mohammed Alamri [a], Bo Liu[b],, Michael Walsh [c], Jennifer Doolin[d], Cindy Berrie[d], and Judy Wu[b]

[a] *Department of Physics, University of Umm Al-Qura, P.O. Box 56335, Makkah 21955, Saudi Arabia*

[b]*Department of Physics and Astronomy, The University of Kansas, Lawrence, Kansas 66045, USA*

[c]*Department of Physics and Astronomy, The University of Kansas, Lawrence, Kansas 66045, USA*

[d]*Department of Chemistry,, The University of Kansas, Lawrence, Kansas 66045, USA*

moomri@uqu.edu.sa

H_2 sensors consisting of a single-wall carbon nanotubes film/graphene 3D electrode decorated with catalytic Pt nanoparticles using atomic layer deposition (ALD Pt-NPs @ SWCNTs/Gr) have been developed. The performance of the H2 sensitivity and response speed was investigated as function of C-band ultraviolet (UVC) radiation time in the range of 0-20 minutes. It has been found that the H_2 gas response can be effectively enhanced by UVC irradiation and the enhancement depends on the accumulated UV irradiation quantitatively. Remarkably, with an UVC irradiation intensity of 4.6 mW/cm2 for 10 minutes on the ALD Pt-NPs @ SWCNTs/Gr sensor, its H_2 gas response was enhanced by 4.4 folds, together with an enhanced response speed by 3.75 times as compared to that of the as-made sensors before the UV irradiation. This enhancement can be attributed to desorption of air molecules adsorbed on the SWCNTs and graphene surfaces upon exposure to ambient. This result has demonstrated the effectiveness of the UVC irradiation as a non-destructive method for ambient operation of the ALD Pt-NPs @ SWCNTs/Gr H_2 sensors with much enhanced performance.

The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

Parallel Symposia Program & Abstract

Industry

Monday, JUNE 20th, 2022

		Chair: Suguru Noda (Waseda University)
14:30-15:00	P-In-I1	**Mitsugu Uejima** (Zeon Corporation, Japan) *Mass production and application development of single-walled carbon nanotubes*
15:00-15:30	P-In-I2	**Peiyu Sun** (Jiangsu Shanyuan Technology Co., Ltd, China) *New generation graphene conductive slurry for LIB application and its development trend*
15:30-15:40	Short break	
		Chair: Geon-Woong Lee (KERI)
15:40-16:10	P-In-I3	**Hakmin Lee** (HNS Co. Ltd., Korea) *Silicon/Graphene Composite Anode Material for High Capacity Li-Ion Batteries*
16:10-16:40	P-In-I4	**Taneli Juntunen** (Canatu, Finland) *The most advanced carbon nanotubes for industry-transforming products*
16:40-17:00	P-In-C1	**Hee Jin Jeong** (KERI, Korea) *Copper/graphene hybrid materials-based conductive inks for environmentally stable printed electrodes*

Mass production and application development of single-walled carbon nanotubes

Mitsugu Uejima
CNT Division / CNT Laboratory, Zeon Corporation,
1-6-2 Marunouchi, Chiyoda-ku, Tokyo, 100-8246, JAPAN
M.Uejima@zeon.co.jp

Since its discovery by Dr. Iijima in 1993 [1], single-walled carbon nanotubes (SWCNTs) have been considered for various products due to their excellent characteristics. In 2004, Dr. Hata et al at the National Institute of Advanced Industrial Science and Technology (AIST) developed an innovative method for the synthesis of SWCNTs [2]. The discovery of the "super growth method" provided a major breakthrough in the mass production of SWCNTs.

We have been participating in a Japanese national project since 2006 to develop mass production technology for single-walled carbon nanotubes based on the "super growth method", and we started operation of a mass production plant for single-walled carbon nanotubes in 2015. SWCNTs made by the super growth method, SGCNTs, have some unique characteristics such as high aspect ratio (length), high purity, and high surface area, and can be mixed with polymers or elastomers to be able to add various functions as composite materials. For example, by adding a small amount of SGCNTs to silicone rubber, it is possible to create a composite material that ~~is~~ possesses both electrically conductive and stretchable behaviors. Such composite materials allow us to design stretchable devices and are expected to be commercialized in near future. By adding SGCNTs to fluoro-elastomers, highly heat-resistant rubber composites can be fabricated, which are expected to be applied to sealing for oil drilling rigs and sealing for high-temperature parts of chemical plants.

It is considered that the excellent characteristics of SGCNTs enable us to develop next-generation energy storage devices and electronic devices. As an energy storage device, SGCNTs can be applied as a cathode material for lithium-air batteries which show excellent properties ever before [3]. SGCNTs are also suitable as a material for CNT-based nonvolatile memory (NRAM), which is being developed for social implementation through the Japan National Project.

[1] S. Iijima and T. Ichihashi: Nature 388, 756 (1993).
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[3] A. Nomura, E. Mizuki, K. Ito, Y. Kubo, T. Yamagishi, M. Uejima, Electrochimica Acta. 400, (2021).

New generation graphene conductive slurry for LIB application and its development trend

Peiyu Sun

Jiangsu Shanyuan Technology Co., Ltd.

Building 15, No. 666, Dailuo Road, Changzhou Economic Development Zone, Changzhou City, Jiangsu Province, China 213102

sunpeiyu@shanshan.com

The development of carbon materials as conductive additives used in lithium-ion battery (LIB) is introduced, including the update trend of graphene conductive slurry as conductive additive. In addition to carbon black, muti-wall carbon nanotube (MWCNT) conductive slurry and common graphene conductive slurry are widely used as conductive additives for LIB in China and have exploded in recent years for the excellent conductivity with benefit of reducing the internal resistance and improving the energy density, rate and cycle performance.

Lately, with the control of thickness, defects, and particular size of graphene sheets, new generation graphene conductive slurry has been developed, exhibiting wonderful performance as conductive additive in LIB, not only in LIB based on $LiFePO_4$ (LFP) cathode, but also in LIB based on $LiNi_xMn_yCo_zO_2$ (NMC)cathode. The electrode resistivity based on new generation graphene slurry is much lower than that based on common graphene slurry. SEM observation of cathode electrode shows that the new generation graphene sheets with thin thickness are well attached to the surface of the active materials, and also bridge conductive channels among active materials.

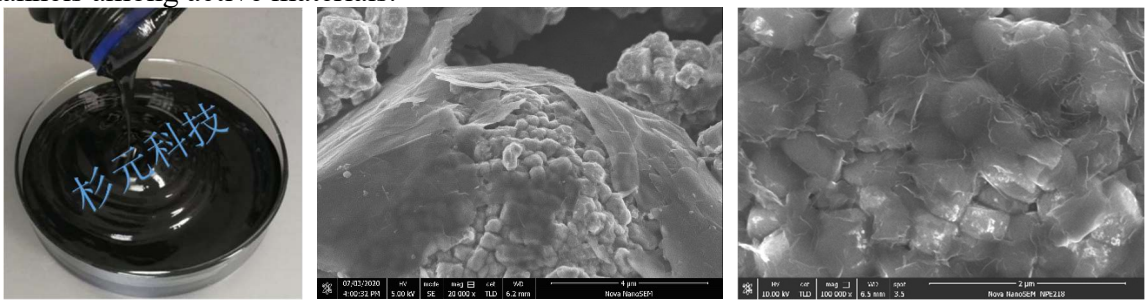

Fig 1. Graphene conductive slurry (left), common graphene sheets in NMC electrode (middle), new generation graphene sheets in NMC electrode (right)

With comparison to carbon nanotube slurry for LIB, the conductivity of the developed new generation graphene slurry has surpassed the current mainstream MWCNT slurry and is close to single-wall carbon tubes (SWCNT) slurry. Due to the absolute price advantage compared with SWCNT and conductivity advantage compared with MWCNT, the new generation graphene conductive slurry is quickly commercialized and sold in large scale in China.

In the future, similar to the development of carbon nanotube conductive slurry (from MWCNT with large tube diameter, to MWCNT with fine tube diameter, and then to SWCNT with tube diameter at 1-2nm), the next generation of graphene conductive slurry based on 2-3-layer graphene may challenge or surpass SWCNT conductive slurry in LIB application.

Silicon/Graphene Composite Anode Material for High Capacity Li-Ion Batteries

Hakmin Lee [a]

[a] *HNS Co. Ltd., Gyeonggi-do 12790, Republic of Korea*

hakimlee@hnss.co.kr

Silicon is one of the most attractive anode materials for Li-ion battery (LIB) system, because of high theoretical capacity (4200 mAh/g), which is 10 times higher than commercialized graphite anode (372 mAh/g). However, the large volume expansion (>300%) of Si electrodes during the lithium ion insertion/extraction process leads to a rapid decay of the reversible capacity and it is currently a hot research topic, not only in academia but also in industry. In this talk, we report a new strategy for overcoming the technical issue of silicon anode materials using graphene. The anode materials of Silicon/Graphene composite was simply prepared by facile spray drying method. In this material system, the high quality graphene 2D sheet in Silicon/Graphene core-shell structure effectively prevents the direct contact of silicon with the electrolyte, efficiently suppress the growth of thick SEI (solid electrolyte interface) layers on silicon. As a results, the electrochemical performance in cyclic stability of Silicon/Graphene composite anode was much improved. Here, our graphene prepared by a solution process has of high conductivity (> 70,000 S/m), aqueous dispersion stability and low surface area (<100 m2/g), which are three distinct characteristics from other commercialized graphene products and play a key role to improve the cyclic stability.

The most advanced carbon nanotubes for industry-transforming products

Dr. Taneli Juntunen
Canatu
Tiilenlyöjänkuja 9 A, FI-01720 Vantaa, Finland
taneli.juntunen@canatu.com

Carbon is the most versatile material in the universe. We create the most advanced carbon nanotubes, allowing us to work with forerunner companies in diverse industries.

Canatu's proprietary carbon nanotube (Canatu CNT) technology is based on the unique dry floating catalyst chemical vapor deposition (FC-CVD) process. The process ensures consistent record-breaking quality of CNTs, as proven by our experience in mass production for the automotive industry since 2015 and for the semiconductor industry since 2021.

The broad applicability of Canatu CNTs is attributed to our leading control over the CNT synthesis and industrial manufacturing processes. When the remarkable one-dimensional intrinsic properties of virtually defect-free Canatu CNTs are expanded into a two-dimensional network, the resulting membrane exhibits unequaled combination of optical, thermal, electrical, and mechanical properties, which may be tailored extensively.

Our scalable manufacturing and product platforms – currently transparent conductive films, free-standing CNT membranes, and point-of-care sensing – allow us to develop diverse products with different industries. Today, Canatu mass produces its products for three companies in the automotive and one in the semiconductor industries, with current product portfolio ranging from automotive Advanced Driver Assistance System (ADAS) heaters to capacitive touch sensors to EUV pellicles and beyond.

Fig 1. Canatu CNT is primed for highly engineered solutions

Copper/graphene hybrid materials-based conductive inks for environmentally stable printed electrodes

Jae-Won Lee[a], Jong Hwan Park[a,b], Seon Hee Seo[a], Seung Yol Jeong[a,b], Joong Tark Han[a,b], Geon-Woong Lee[a] and Hee Jin Jeong[a,b,*]

[a] *Nano Carbon Materials Research Group, Korea Electrotechnology Research Institute (KERI), Changwon 51543, Republic of Korea*

[b] *Department of Electro-Functionality Material Engineering, University of Science and Technology (UST), Changwon 51543, Republic of Korea*

[*] *wavicle11@keri.re.kr*

Solution-processable conductor materials that can be combined with various printing techniques have recently attracted increasing interest for use in low cost, high performance integrated electronics. The metallic nanoparticle inks, mostly based on Ag and Au, are adequate solution processable materials satisfying the requirements such as low-temperature processability, high conductivity, and environmental stability. The high cost involved in synthesizing Au and Ag nanoparticles, however, has overshadowed these advantages. Cu nanoparticles are considered to be a viable alternative in terms of their inexpensive chemical synthesis pathway and, in principle, low electrical resistivity comparable to that of noble metals (Au, Ag). However, the presence of a surface oxide layer, even with thickness below a few nanometers, critically degrades the electrical properties of Cu nanoparticle-based conductive layers. Here we introduced environmentally stable Cu nanoparticle-based conductive fillers by covering the graphene layer. The electrical and mechanical properties of Cu/graphene-core/shell hybrid materials as well as environmental stability are discussed.

The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

Parallel Symposia Program & Abstract

Spectroscopy

Parallel Symposia **SPECTROSCOPY @ N-Center # 86120**

Tuesday, JUNE 21st, 2022

		Chair: Sofie Cambré (University of Antwerp)
14:30-15:00	P-SP-I1	**Sebastian Heeg** (Humboldt Universität zu Berlin, Germany) Raman spectroscopy of single carbyne chains confined in CNTs
15:00-15:30	P-SP-I2	**Kaihui Liu** (Peking University, China) *Optical Spectroscopy of Individual Carbon Nanotubes*
15:30-15:40	Short break	
		Chair: Sunmin Ryu (POSTECH)
15:40-16:10	P-SP-I3	**Sang-Yong Ju** (Yonsei University, Korea) *Raman Enhancement of Copper Phthalocyanine Promoted by Excited State Charge Transfer of Twisted Bilayer Graphenes*
16:10-16:40	P-SP-I4	**Laura Kim** (California Institute of Technology, USA) Bright Hot Plasmons Emitted from Non-Equilibrium Electronic States in Graphene
16:40-17:00	P-SP-C1	**Ji-Hee Kim** (Sungkyunkwan University, Korea) *Hot-carrier photovoltaics in MoS2/Graphene heterostructures*

Raman spectroscopy of single carbyne chains confined in CNTs

Sebastian Heeg
Institut für Physik, Humboldt Universität zu Berlin
Newtonstr. 15, 12489 Berlin, Germany
sebastian.heeg@physik.hu-berlin.de

Carbyne by definition is an infinite linear chain of carbon atoms that forms the truly one-dimensional allotrope of carbon. The exploration of carbyne and its properties, however, has long been hindered by its extreme chemical instability and short chain lengths far below the threshold of 100 atoms for which finite linear carbon chains mimic the properties of carbyne. A breakthrough was achieved in 2016 with the synthesis, stabilization and study of individual carbyne chains comprising of thousands of atoms inside double-walled carbon nanotubes. [1]

I this talk, I will present recent advances in the spectroscopy of individual carbyne chains confined inside carbon nanotubes with tip-enhanced and wavelength-dependent Raman spectroscopy by us and other researchers [2,3]. We will discuss the role of the nanotube hosts in determining the electronic and vibronic structure of the confined carbyne chains, carbyne's intense Raman response and why single carbyne chains need to be studied [4,5]. Finally, I will review open questions in confined carbyne research and how these questions can be addressed.

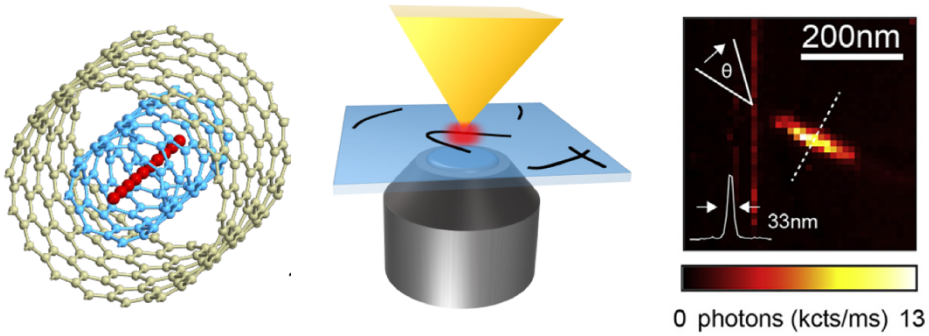

Fig1. Confined carbyne inside a double-walled carbon nanotube, we which probe and image with nanoscale spatial resolution by tip-enhanced Raman spectroscopy. From [2,3].

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Optical Spectroscopy of Individual Carbon Nanotubes

Kaihui Liu*

School of Physics, Peking University, Beijing 100871, China

*Corresponding author(s): khliu@pku.edu.cn

The development and application of high-performance materials have greatly promoted the development of the semiconductor industry and information technology. From the first-generation semiconductor of silicon, the second-generation of gallium arsenide to the third-generation of gallium nitride, all of them have promoted significant improvements in the performances of the electronic and optoelectronic devices. Now we are entering a "post-Moore" era, carbon nanotube (CNT)-based electronics are highly desired to replace Si complementary metal-oxide-semiconductor (CMOS) technology, which will soon meet its performance limit. To truly apply CNT to the construction of next-generation devices, high-throughput and non-invasive characterization on their accurate structure and physical properties is a prerequisite. In this talk, I will introduce our recent developed optical techniques for complex optical susceptibility measurement[1] and handedness characterization[2] of individual carbon nanotubes. The complete optical response and structural characterization at the single-tube level should accelerate applications of CNT-based electronics and optoelectronics and the developed optical systems materials are expected to be applied to various one-dimensional nanomaterials.

Reference

1. Kaihui Liu* et al. "Measurement of complex optical susceptibility for individual carbon nanotubes by elliptically polarized light excitation", *Nature Communications*, **9**, 1 (2018).
2. Kaihui Liu* et al. "Complete structural characterization of single carbon nanotubes by Rayleigh scattering circular dichroism", *Nature Nanotechnology,* **16,** 10 (2021).

Raman Enhancement of Copper Phthalocyanine Promoted by Excited State Charge Transfer of Twisted Bilayer Graphenes

Sang-Yong Ju*

Department of Chemistry, Yonsei University, Seoul 03722, Republic of Korea

Corresponding Address

syju@yonsei.ac.kr

Few atom thick, twisted bilayer graphene (tBLG) possesses a rotation angle (θ) dependent van Hove singularity (vHs). Fine-tuning vHs serves a potential method to enhance charge transfer (CT) in surface enhanced Raman spectroscopy. This study shows that tBLG having a specific θ promotes as high as a 1.7 times enhancement of the Raman signals of copper phthalocyanine (CuPc) as compared to that caused by single layer graphene (SLG). The results of a combination of reflection imaging spectroscopy and widefield Raman provide spatial and spectral information about both tBLG with θ ranging from 10.9 to 13.7° and the corresponding vHs. Comparison of Raman spectra of CuPc in presence and absence of tBLG demonstrates that a significant enhancement of certain CuPc vibrational modes occurs when the underlying tBLG possesses a θ = 12.2°, showing as high as 6.8 and 1.7 times enhancements of certain vibrational mode as compared to those of CuPc on bare and SLG substrates, respectively. Theoretical calculations indicate that a match between the energies of vHs of tBLG with those of frontier orbitals of CuPc facilitates CT from the distant SLG to CuPc.

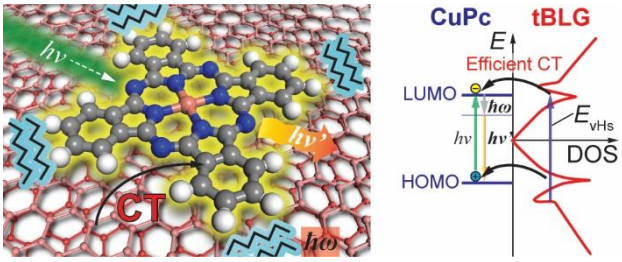

Fig 1. Excited charge transfer promoted Raman enhancement of CuPc by tBLG

Bright Hot Plasmons Emitted from Non-Equilibrium Electronic States in Graphene

Laura Kim[a,b], Seyoon Kim[a,c], Pankaj K. Jha[a], Victor W. Brar[a,c], Harry A. Atwater[a]

[a]*Thomas J. Watson of Applied Physics, California Institute of Technology, Pasadena, California 91125, USA*
[b]*Research Laboratory of Electronics, M. I. T, 50 Vassar Street, Cambridge, MA 02139, USA*
[c]*Department of Physics, University of Wisconsin-Madison, Madison, WI 53711, USA*
lbkim@mit.edu

The decay dynamics of excited carriers in graphene have attracted wide scientific attention, as the gapless Dirac electronic band structure opens up relaxation channels that are not allowed in conventional materials. I will present the first experimental demonstration of a mid-infrared light-emitting mechanism originating from an ultrafast coupling of optically excited carriers into hot plasmon excitations in graphene [1]. Such excitations show gate-tunable, non-Planckian emission characteristics due to the atom-level confinement of the electromagnetic states. The brightness of hot plasmon emission is several orders of magnitude higher than the spontaneous emission of light from a hot electronic bath of similar temperature – several 1000s of Kelvins (Fig. 1b). Nanophotonic engineering of a graphene surface can harness such brightness by enhancing coupling between emitted plasmons and free-space light. Calculations for our experimental conditions indicate that conditions for plasmon gain exist on the sub-ps timescale during which stimulated plasmon emission dominates spontaneous plasmon emission. These findings for plasmon emission in photo-inverted graphene open a new path for the exploration of mid-infrared emission processes, and this mechanism can potentially be exploited for both far-field and near-field applications for strong optical field generation.

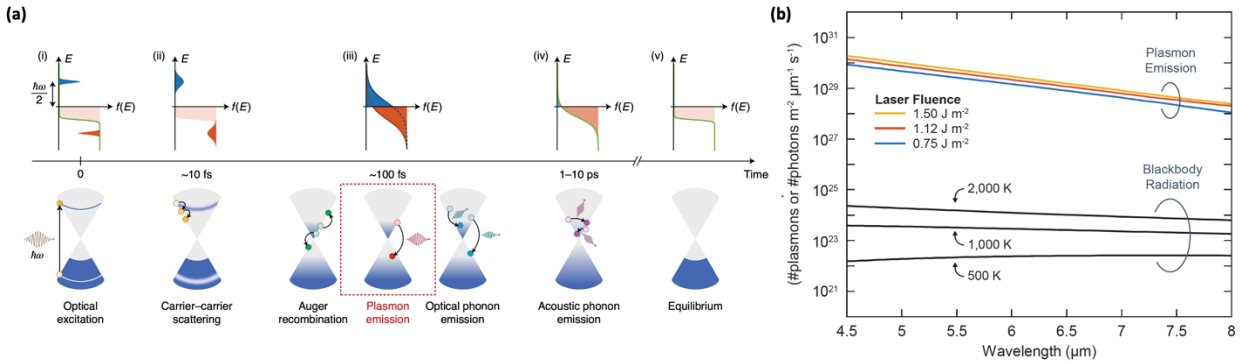

Fig. 1 (a) Carrier relaxation processes in graphene under ultrafast optical excitation with corresponding carrier distributions. (b) Spectral flux of cumulative spontaneous plasmon emission assuming unity out-coupling efficiency at various laser fluences for a given graphene Fermi level of 0.34 eV compared with the spectral flux of blackbody emission at 500 K, 1,000 K and 2,000 K radiated over all solid angles.

Reference

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Hot-carrier photovoltaics in MoS_2/Graphene heterostructures

Ji-Hee Kim

Department of Energy Science, Sungkyunkwan University, Republic of Korea.
Center for Integrated Nanostructure Physics, Sungkyunkwan University, Republic of Korea.
Institute for Basic Science, Republic of Korea.

Corresponding Address
kimj@skku.edu

One of the key-aims for enhancing the performance of advanced optoelectronic devices is to convert photoexcited hot carriers to electricity in semiconductors. To realize efficient hot carrier devices, efforts focus on elongating the relaxation time of hot carriers and on understanding the dynamics of hot carriers at the interface between 2D material and metal electrode. Here, we investigated an efficient interfacial hot carrier transfer from MoS_2 to graphene in their heterostructure with a prolonged relaxation time using broadband transient absorption spectroscopy [1,2]. We observed four times slower relaxation time of graphene in the heterostructure, which is attributed to the enhanced hot optical phonon bottleneck effect of graphene by an increased photoexcited carrier population. Furthermore, by integrating graphene with MoS_2, we demonstrated an efficient hot carrier solar cell device in MoS_2/graphene heterostructure.

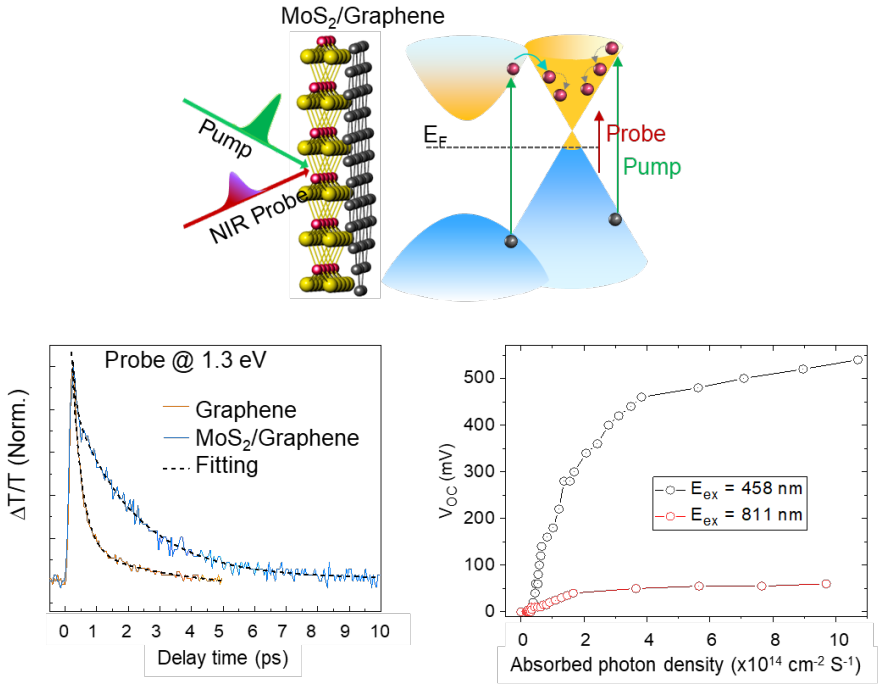

Fig 1. Hot carrier cooling dynamics and photovoltaic performance in MoS_2/graphene heterostructure

[1] ACS Nano 14, 13905 (2020)

[2] Nature Reviews Physics 3, 178 (2021)

The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

Parallel Symposia Program & Abstract

Energy

Parallel Symposia **ENERGY @ N-Center # 86120**

Thursday, JUNE 23rd, 2022

		Chair: Jong Hun Han (Chonnam National University)
14:30-15:00	P-En-I1	**Jong Beom Baek** (UNIST, Korea) *Mechanochemistry for Materials Synthesis*
15:00-15:30	P-En-I2	**Michael De Volder** (University of Cambridge, UK) *Low Dimensional Materials for Light-Enhanced Energy Storage Devices*
15:30-15:40	Short break	
		Chair: Seokwoo Jeon (KAIST)
15:40-16:10	P-En-I3	**Fei Wei** (Tsinghua University, China) *Large Scale Synthesis of Single and Bundled Defect-free Carbon Nanotubes and Its Mechanical Behavior*
16:10-16:40	P-En-I4	**Morinobu Endo** (Shinshu University, Japan) *Applications of Carbon Nanotubes toward Energy and Sustainability*
16:40-17:00	P-En-C1	**Yoonbin Kim** (Sungkyunkwan University, Korea) *Na-Coordinated Polymeric Phthalocyanines as Stable High-Capacity Organic Anodes for Sodium-Ion Batteries*

Friday, JUNE 24th, 2022

		Chair: Sang Ouk Kim (KAIST)
13:15-13:45	P-En-I5	**Hyoyoung Lee** (Sungkyunkwan University, Korea) *Selective Disordering of Rutile Phase-only and Anatase Phase-only in P25 TiO2 for Visible-light Photocatalyst*
13:45-14:15	P-En-I6	**Hong Jin Fan** (Nanyang Technological University, Singapore) *Carbon fibers and tubes for stable Zn anode and flexible devices*
14:15-14:25	Short break	
		Chair: Michael De Volder (University of Cambridge)
14:25-14:45	P-En-C2	**Dimitrios Perivoliotis** (Umeå University, Sweden) *Cation (Li+, Na+, Co2+) intercalated 1T-MoS2 on carbon nanotubes as hydrogen evolution electrocatalyst in proton exchange membrane (PEM) water electrolyzer*
14:45-15:05	P-En-C3	**Mariam Ezzedine** (IPParis, France) *New Hybrid Nano-Architecture of Sulfur Electrode for Lithium-Sulfur Batteries.*

Mechanochemistry for Materials Synthesis

Jong-Beom Baek
Ulsan National Institute of Science and Technology
50 UNIST, Ulsan 44919, South Korea
jbbaek@unist.ac.kr

Mechanochemistry is related to the chemical reactions caused by mechanical energies, which can generate chemically active species by mechanical abrasion, friction, cracking, cavitation and so on. One of the representative tools for mechanochemistry is ball-milling, which can offer a new method for materials syntheses, including ammonia, methane and single atom catalysts (SACs). Ammonia is mainly produced by the Haber-Bosch process, which has been used for over 110 years. However, the Haber-Bosch process cannot be performed in mild conditions, because of kinetic reasons. We discovered a new method for the synthesis of the ammonia under mild conditions (45 °C and 1 bar) *via* mechanochemical ball-milling iron (Fe) powders in the presence of nitrogen and hydrogen (Fig. 1).[1] With this new process, the final concentration of ammonia reaches 82.5 vol%, which is higher than the state-of-art Haber-Bosch process (25 vol%) under high temperature and pressure (450 °C and 200 bar). Mechanochemically induced high-density defects and violent impact on the Fe catalysts are responsible for the mild synthesis conditions.[2] The conversion of carbon materials in to methane can be extremely enhanced by ball-milling in the presence of hydrogen.[3] The reaction rate of carbon hydrogasification is four orders of magnitude higher than the conventional thermal method. Various SACs can also be produced by a top-down mechanochemical abrasion method, in which the bulk metal balls are directly atomized onto different supports, such as carbon frameworks, oxides, and nitrides.[4]

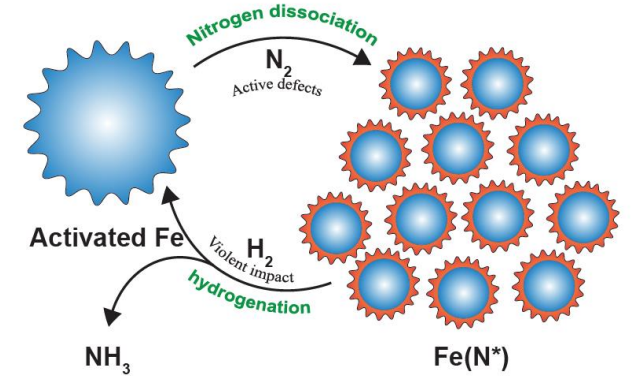

Fig. 1. Schematic illustration of the ammonia synthesis process.

1. Han, *et al., Nat. Nanotechnol.,* **16** (2021), 325-330.
2. Han, *et al., Sci. Adv.*, **5** (2019), eaax8275.
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4. Han, *et al., Nat. Nanotechnol.*, **16** (2022), 325-330.

Low Dimensional Materials for Light-Enhanced Energy Storage Devices

Michael De Volder
University of Cambridge
17 Charles Babbage Rd, CB30FS Cambridge, UK
Mfld2@cam.ac.uk

Systems for harvesting and storing solar energy are used for applications ranging from large scale solar farms to small autonomous devices. Typically these devices combine solar cells for light harvesting with rechargeable batteries to temporarily store the solar energy. Rather than having a separate energy harvesting and storage devices, photo-enhanced batteries are a new type of devices that combine both functionalities. This technology may reduce both the cost and volume of solar energy solutions.

This presentation will discuss how low dimensional 2D (Perovskites and MoS_2) and 1D (V_2O_5 and VO_2) nanomaterials allow to design new light enhanced batteries and capacitors. These materials are selected because they allow to both store energy and harvest light at the same time. Achieving a light enhanced device performance typically requires the design of a photoactive cathode composed of a layer-by-layer design of charge transport and energy storage layers. I will show how a careful selection of the active materials and engineering their interfaces allows for improving the device efficiency and cycle life. Interestingly, these concepts can be used for Zn-Ion and Li-Ion batteries as well as different capacitor designs. Light-enhanced energy storage devices are in particular attractive to fight energy poverty, and therefore low-cost embodiments of this technology will be reviewed.

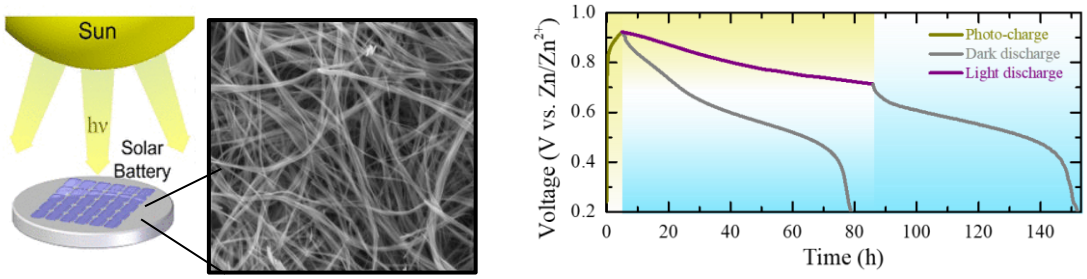

Fig 1. Left: Schematic of a light-enhanced battery and V_2O_5 nanrods used in light enhanced-batteries. Right: Measurements of a light-enhanced battery under different illumination conditions

Large Scale Synthesis of Single and Bundled Defect-free Carbon Nanotubes and Its Mechanical Behavior

Fei Wei i

Beijing Key Laboratory of Green Chemical Reaction Engineering and Technology, Department of Chemical Engineering, Tsinghua University, Beijing 100084, China.

Wf-dce@tsinghua.edu.cn

Super-strong materials can be utilized in many fields such as bulletproof vest, airframe, suspension bridge, flywheel energy storage, etc. As one of the strongest materials, carbon nanotubes (CNTs) can potentially be used to fabricate super-strong fibers. However, the tensile strength of CNTs is impaired a lot by defects, and the CNT fibers prepared so far have strength much lower than that of a single CNT, showing a "size effect". The conventional study of solid mechanics is usually based on the assumption that materials contain defects. Defect-free ultralong CNTs can hopefully help us avoid the "size effect" of nanomaterials and produce super-strong CNT fibers. They would also provide a system for the study of the mechanical behavior of ideal solids.

In this talk, we discuss our recent studies on the mechanical behavior of defect-free single CNTs and CNT bundles. First, we introduce the defect-free structure of ultralong CNTs, which is one type of ideal solid. Second, we review the investigation of the static tensile properties and dynamic fatigue resistance and their temperature-dependence of single centimeters long defect-free CNTs. The results showed that defect-free CNTs have superior comprehensive mechanical properties, including super-strength, -toughness and -durability. Different from traditional materials, the fatigue lifetime and fracture of CNTs are dominated by the first single-bond-sized defect, showing "super-brittleness" at low temperature with non-local behavior. Third, by using a gas flow focusing *in situ* synthesis method as well as a synchronous-tightening-and-relaxing strengthening strategy, we successfully fabricated CNT bundles with tensile strength approaching that of single CNTs and showed that the "size effect" can be avoided. In addition, the advantages and promising future of using CNTs in flywheel energy storage are discussed..

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Applications of Carbon Nanotubes toward Energy and Sustainability

Morinobu Endo
Research Initiative for Supra-Materials, Shinshu University, Japan
4-17-1, Wakasato, Nagano, 380-8553 JAPAN
E-mail: endo@endomoribu.shinshu-u.ac.jp

Carbon nanotubes (CNT) have been contributing to various fields of technology because of their outstanding physical and chemical performances owing to their intrinsic nano-sized and one-dimensional nature of carbon. The most common process to synthesize carbon nanotubes is CCVD method for multi-walled, double-walled and single-walled structure, because this technique is very powerful process for large scale production and controllability of the nanostructure. CCVD method is based on the nano-sized iron catalytic particles that are either dispersed on the growing substrate or floated in the reaction chamber [1-4].

World is facing many emerging concerns such as global warming, constant shortage of water and exhaustion of natural resources, which are the current major issues for sustainability. Therefore, finding measures for the resolution of such issues have been required. In this account, we believe that carbon nanotubes have enough potential to contributing to these issues. Here, applications of carbon nanotubes relating the energy and sustainability will be demonstrated.

Firstly, the current usage of carbon nanotubes in energy storage devices as one of the important components of lithium ion secondary batteries is shown [5,6]. Mainly, the effectiveness of the carbon nanotube additive to both cathode and anode electrode on the performance of lithium ion batteries is shown, which has been highly promoted by the coming electric vehicles era. Secondly, the industrial usage of carbon nanotubes as multi-functional filler in polymer composites such as functional rubber, water desalination membranes and anticorrosion paint will be summarized, by focusing to water treatment reverse osmosis membrane [7,8]. Thirdly as natural resources sustainability, the conductive wire application will be demonstrated.

Finally, for further successful developments of CNTs, the safety of carbon nanotubes is the most important issue [9-12]. Sharing openly all the information on the risks and benefits of carbon nanomaterials with all the stakeholders is essential. By responsible productions and uses and designing the safer nanostructure based on accumulated CNTs science, we are able to promote further the applications of CNTs in order to contribute to world sustainability.

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[**7]** S. Inukai1, R. C. Silva, J. O. Medina, A. M. Gomez, K. Takeuchi, T. Hayashi, A. Tanioka, T. Araki1, S. Tejima, T. Noguchi, M. Terrones, M. Endo, High-performance multifunctional reverse osmosis membranes obtained by carbon nanotube·polyamide nanocomposite, ***Scientific Reports* 5**, Article number: 13562 (2015),
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Na-Coordinated Polymeric Phthalocyanines as Stable High-Capacity Organic Anodes for Sodium-Ion Batteries

Yoonbin Kim [a, b], Ho Seok Park [b]

[a] *Convergence Research Center for Energy and Environmnetal Sciences, Sungkyunkwan University, Suwon 16419, South Korea*

[b] *Center for 2D Redox Energy Storage, Sungkyunkwan University, Suwon 16419, South Korea*

yoonbin.kim@skku.edu

Sodium-ion batteries (SIBs) have attracted considerable interest as an alternative to lithium-ion batteries owing to their similar electrochemical performance and superior long-term cycle stability. Organic materials are regarded as promising anode materials for constructing SIBs with high capacity and good retention. However, utilization of organic materials is rather limited by their low energy density and poor stability at high current densities. To overcome these limitations, we utilized a novel polymeric disodium phthalocyanines (*p*NaPc) as SIB anodes to provide stable coordination sites for Na ions as well as to enhance the stability at high current density. By varying the linker type during a one-pot cyclization and polymerization process, two *p*NaPc anodes with O- (O-*p*NaPc) and S-linkers (S-*p*NaPc) were prepared, and their structural and electrochemical properties were investigated. The O-*p*NaPc binds Na ions with a lower binding energy compared with S-*p*NaPc, which leads to more facile Na-ion coordination/dissociation when engaged as SIB anode. The use of O-*p*NaPc significantly improves the redox kinetics and cycle stability and allows the fabrication of a full cell against $Na_3V_2(PO_4)_2F_3$/C cathode, which demonstrates its practical application with high energy density (288 Wh kg^{-1}) and high power density (149 W kg^{-1}).

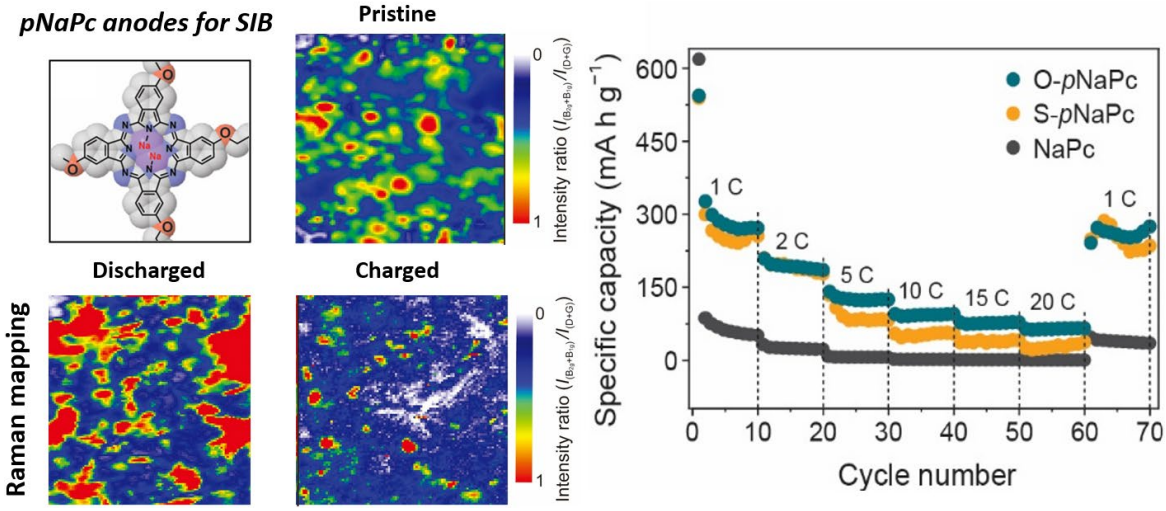

Fig 1. Illustration of polymeric disodium phthalocyanine (pNaPc) anodes and their electrochemical performances.

Selective Disordering of Rutile Phase-only and Anatase Phase-only in P25 TiO2 for Visible-light Photocatalyst

Hyoyoung Lee[1,2]

[1]Center for Integrated Nanostructure Physics, Institute for Basic Science (IBS), Sungkyunkwan University, Suwon, Republic of Korea. [2]Department of Chemistry, Sungkyunkwan University, Suwon, Republic of Korea.

hyoyoung@skku.edu

Titanium oxide (TiO_2) is a well-known photocatalyst. We like to report visible-light-driven two different types of blue-colored TiO_2 (or "blue titania") nanoparticles that could absorb visible light thanks to a reduced bandgap of about 2.7 eV. They were made of phase-selectively ordered anatase/disordered rutile (A_o/R_d) P25 TiO_2 that is reduced from Li-ethylene diamine solution [1], and phase-selectively disordered anatase/ordered rutile (A_d/R_o) P25 TiO_2 that is reduced from Na, K-ethylene diamine solution [2]. The introduction of the only one-phase disorder from the two mixed phases remarkably enhances the photocatalytic performances including water splitting [1], CO_2 reduction [2,3], and nitrogen reaction [4], which is proved by the modulated band alignments of two blue TiO_2 [5].

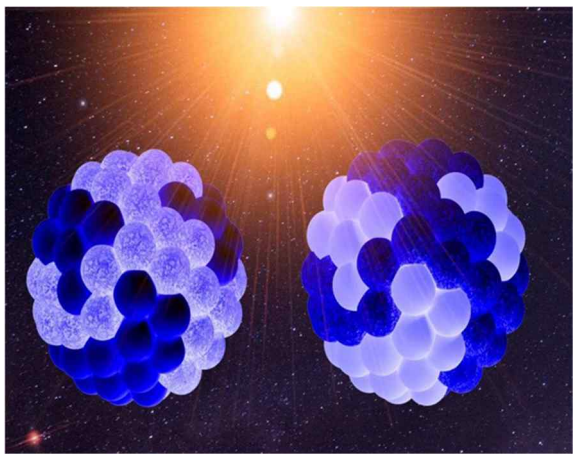

Figure 1. Phase-selectively disordered P25 TiO_2 (Called Hyoyoung Lee's blue TiO_2)

A Z-schemed photocatalyst that is combined with a high reductive blue (A_o/R_d) TiO_2 and high oxidative tungsten trioxide (WO_3) shows high performances in various fields [6].

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Carbon fibers and tubes for stable Zn anode and flexible devices

Hongjin Fan
Nanyang Technological University
School of Physical and Mathematical Sciences, 21 Nanyang Link, 637371 Singapore
fanhj@ntu.edu.sg

My talk will focus on two topics, which are both related to electrospun carbon fibers in energy storage. The first work is about porous carbon fibers in flexible energy storage devices [1], and stable Zn anode for long-lifespan aqueous Zn-ion batteries [2]. The second work is about achieving a balance between high volume density and pore utilization of tubular carbon electrodes [3]. Capillary force is employed to convert hollow carbon fibers to a highly compact and interwoven flexible electrode. The volume of the electrode can be decreased by 96% without sacrificing the gravimetric capacity. Importantly, the conductivity of the compact carbon electrode can reach up to 50,500 S/m and the Young's modulus of the electrode increases by 105 times. This may provide a high-volume-density electrode for both batteries and hybrid capacitors.

This research is supported from Singapore Ministry of Education by Tier 2 grant (T2EP50121-0012).

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Cation (Li^+, Na^+, Co^{2+}) intercalated 1T-MoS_2 on carbon nanotubes as hydrogen evolution electrocatalyst in proton exchange membrane (PEM) water electrolyzer

Dimitrios K. Perivoliotis[a], Alexis Piñeiro-García[a], Eduardo Gracia-Espino[a], Thomas Wågberg[a]
[a] Department of Physics, Umeå University, Umeå 90187, Sweden
dimitrios.perivoliotis@umu.se

The sustainable production of renewable fuels, including hydrogen, is central to eliminate the CO_2 emissions and therefore to moderate the climate change effects. In this regard, proton exchange membrane (PEM) water electrolysis has attracted considerable attention as a CO_2-free technology for hydrogen generation, especially when integrated with renewable energy sources. Presently, the high cost and the scarcity of noble metals that are used to catalyze the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER) restrict the widespread application of the PEM water electrolyzer technology [1]. In the quest for alternative catalyst materials, layered molybdenum disulfide (MoS_2) based materials have been proposed as alternative HER electrocatalysts. Furthermore, it has been demonstrated that the intercalation of metal cations is an effective strategy to stabilize the metastable but highly active towards HER 1T MoS_2 phase [2]. Lithium ions is the most common intercalation agent used; however, recent studies have shown that the intercalation of other metal cations into the interlayer region of 1T-MoS_2 can also lower the HER overpotential [3]. Despite MoS_2-based materials have been widely explored as HER electrocatalysts through half-cell electrochemical tests, only few studies aimed at evaluating their performance under real operating conditions in PEM water electrolyzers.

Herein, we prepared an array of cation (Li^+, Na^+ and Co^{2+}) intercalated 1T-MoS_2 sheets / carbon nanotubes hybrids through a scalable sonication-assisted lithium intercalation approach followed by a solution-based procedure to exchange Li^+ with Na^+ or Co^{2+}[3-4]. The successful synthesis was confirmed via advanced imaging tools and complementary spectroscopic techniques. The HER performance of all materials was thoroughly examined using half-cell electrochemical tests and a PEM electrolyzer with reference to industrial applicable reaction conditions. Insights on the reaction kinetics were obtained via impedance measurements at the low-current region while the long-term stability was also investigated. Notably, the PEM electrolyzer results were consistent with those obtained via the half-cell tests, highlighting that the cation intercalation can significantly promote the HER performance of MoS_2 by stabilizing the 1T-MoS_2 polymorph. Overall, these results pave the way for the further use of MoS_2 based materials as HER electrocatalysts in industrial-scale PEM water electrolyzers.

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New Hybrid Nano-Architecture of Sulfur Electrode for Lithium-Sulfur Batteries.

Ezzedine M, Jardali F, Florea I, Cojocaru C-S

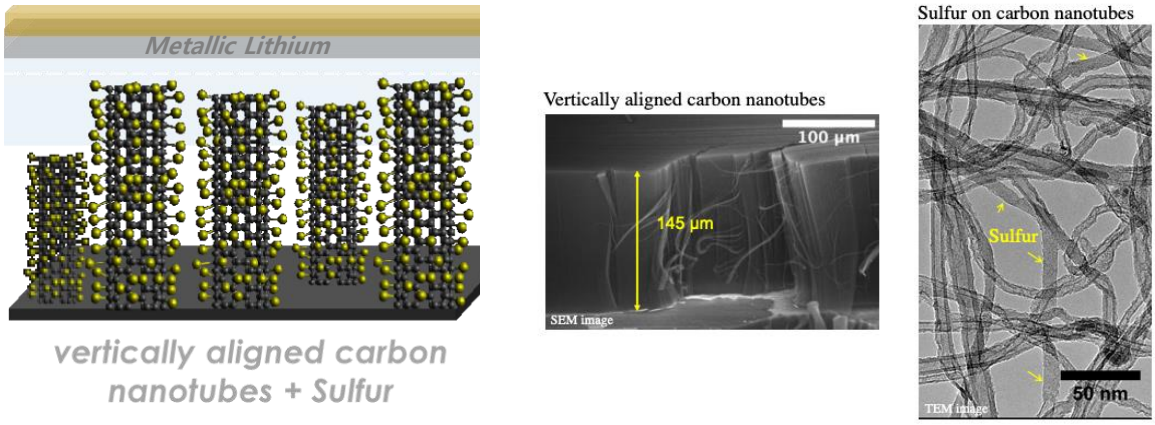
Laboratory of Physics of Interfaces and Thin Films-CNRS UMR 7647, Ecole Polytechnique-IPParis

Route de Saclay, 91128 Palaiseau, France

mariam.ezzedine@polytechnique.edu

Lithium-Sulfur batteries have the potential to provide a much greater energy storage capacity than current Lithium-ion batteries. However, Lithium-Sulfur batteries are hampered by challenges arising from the cell level, such as poor conductivity of sulfur, its volume expansion, and the lithium polysulfides shuttle effect. The technology developed in our lab overcomes these fundamental challenges by implementing an innovative electrode architecture that exploits the properties of vertically aligned carbon nanotubes (VACNTs). The hierarchical-assembled-nanostructured battery positive electrode is based on carbon nanotube carpets grafted by 100% sulfur nanomaterial. Coupling it with metallic lithium as negative electrode results in high energy and power, and long-life Lithium-Sulfur battery (Figure 1). The positive electrode topology enables to store more electrical charge more rapidly than any other commercial electrode, positively impacting the power and energy storage capacity of the battery. The Lithium-Sulfur batteries exclude inactive components (such as binders/additives essential for traditional Lithium-ion batteries), thus eliminating the "dead weight" found in the today's batteries.

Electrochemical performance tests have shown that the Lithium-Sulfur batteries developed in our work have substantially improved capacity performance, stability and cycle life compared to conventional Lithium-Sulfur batteries. At a discharging rate of 2C (i.e., 30 minutes), the cells have shown a stable specific capacity of 400 mAh g^{-1} over 1000 cycles.



(a) (b)

Fig 1. (a) Schematic illustration of the Lithium-Sulfur cell. (b) SEM image of vertically aligned carbon nanotubes on aluminum foil (left) and TEM image of sulfur deposited on carbon nanotube walls (right).

The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

Parallel Symposia Program & Abstract

Low Dimensional Electronics

Parallel Symposia **LOW DIMENSIONAL ELECTRONICS @ Chemistry Building # 330102**

Monday, JUNE 20th, 2022

		Chair: Yutaka Ohno (Nagoya University)
14:30-15:00	P-Lo-I1	**Chul-Ho Lee** (Korea University, Korea) *Interface Band Engineering Toward High-Performance 2D van der Waals Electronics*
15:00-15:30	P-Lo-I2	**Jang Ung Park** (Yonsei University, Korea) *Wearable electronics using nanomaterials*
15:30-15:40	Short break	
		Chair: Sungjoo Lee (Sungkyunkwan University)
15:40-16:10	P-Lo-I3	**Yang Chai** (The Hong Kong Polytechnic University, Hong Kong) *Two-Dimensional Semiconductors for Post-Moore's Law Computing*
16:10-16:40	P-Lo-I4	**Yanqing Wu** (Huazhong University of Science and Technology, China) *High-performance low-dimensional transistors based on ultra-thin body channel materials*
16:40-17:00	P-Lo-C1	**Haomin Wang** (Shanghai Institute of Microsystem and Information Technology, China) *Towards chirality control of graphene nanoribbons embedded in hexagonal boron nitride*

Tuesday, JUNE 21st, 2022

		Chair: Heejun Yang (KAIST)
14:30-15:00	P-Lo-I5	**Sanghoon Bae** (Institute of Materials Science and Engineering, Korea) *Understanding nucleation theory to produce freestanding nanomembranes for artificial heterostructures*
15:00-15:30	P-Lo-I6	**Albert G. Nasibulin** (Skolkovo Institute of Science and Technology, Russia) *Transparent Conducting Films Based on Carbon Nanotubes: Rational Design Towards the Theoretical Limit*
15:30-15:40	Short break	
		Chair: Woo-Jae Kim (Ehwa Womans University)
15:40-16:10	P-Lo-I7	**Chuanhong Jin** (Zhejiang University, China) *An electron microscopy analysis of challenges of carbon nanotube transistors: an electron microscopy viewpoint*
16:10-16:40	P-Lo-I8	**Kosuke Nagashio** (The University of Tokyo, Japan) *Ultrafast 2D nonvolatile memory operation provided by the strong short-Time dielectric breakdown strength of h-BN*
16:40-17:00	P-Lo-C2	**Tzu-Ang Chao** (Taiwan Semiconductor Manufacturing Company, Taiwan) *Small Molecular Additives to Suppress Bundling in Dimension-Limited Self-Alignment Method for High-Density Aligned CNT Arrays*

Interface Band Engineering Toward High-Performance 2D van der Waals Electronics

Chul-Ho Lee[1, 2]

[1]*KU-KIST Graduate School of Converging Science & Technology,* [2]*Department of Integrative Energy Engineering, Korea University, Seoul 02841, Republic of Korea*

Two-dimensional (2D) semiconductors such as transition metal dichalcogenides (TMDs) have emerged as a promising material for implementing beyond-CMOS electronics due to excellent gate coupling and immunity to short channel effects at the ultimate scaling. In addition, owing to a van der Waals (vdW) layered structure, they hold great potential for non-conventional electronics capable of heterogeneous integration and deformation. To achieve high-performance 2D electronic devices, it is highly required to control the electronic states and energy band profiles at various heterointerfaces among the semiconductor channel, the gate dielectric, and metal electrodes. In this talk, I will present two types of proof-of-concept 2D field-effect transistors (FETs) enabled by interface band engineering: 1) modulation-doped FETs (MODFETs) and 2) metal-semiconductor FETs (MESFETs). In a MODFET, we demonstrated remote modulation doping in the type-II band-modulated channel, enabling us to achieve high mobility by suppressing dopant-induced charge impurity scattering [1]. The vdW MESFETs were also demonstrated using the Fermi-level pinning-free metal Schottky gate, whose device characteristics approach the Boltzmann switching limit.

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Wearable electronics using nanomaterials

Jang-Ung Park
Yonsei University
50 Yonsei-ro Seodaemin-gu, Seoul, 03722, South Korea
Jang-ung@yonsei.ac.kr

Recent progress in optoelectronic devices for wearable electronics demands their outstanding mechanical deformability for versatile systems in daily life. Especially, smart contact lenses are one of the promising candidates to provide real-time, noninvasive medical diagnostics from the physiological information on the eye and tear fluid. The eyes contain the tear fluid, so the contact lenses can monitor the physiological status of human body continuously. Previous smart contact lenses have exploited opaque and rigid device components for the operations of these electronic integration systems. Therefore, these devices could interfere with the user's vision and be potentially dangerous to the eyes. Furthermore, the bulky equipment with an excessive cost to monitor the signals from the smart contact lens could restrict the user's activities. These limitations reduce the convenience and features of the smart contact lenses. Therefore, we propose soft smart contact lenses which can detect the biomarker concentrations in tear fluid. For the superior stretchability and transparency, the smart contact lenses are fabricated using metal nanowires and graphene which have stretchable and transparent properties. Therefore, the resulting smart contact lens can provide a clear vision. In addition, the stretchable antenna enables the wireless communication, so the results of biosensors in smart contact lens could be wirelessly monitored. These sensor platforms can be exploited as not only smart contact lenses but also internet of things (IoTs) for the environment monitoring. Furthermore, the smart contact lens integrated with wireless display can exhibit the sensing results through the display pixel and exclude the use of bulky measurement equipment which reduces user convenience. Therefore, we believe that the smart contact lenses suggest a promising strategy towards wearable electronics for the diagnosis of diseases.

Two-Dimensional Semiconductors for Post-Moore's Law Computing

Yang Chai
Faculty of Applied Science and Textile
The Hong Kong Polytechnic University
Email: ychai@polyu.edu.hk

As the Moore's Law is anticipated to flatten in the near term, it requires an investment in both basic sciences (including materials science) and computation paradigms to foster continued technology development in microelectronics. Two-dimensional (2D) layered semiconductors possess atomic level thickness, dangling-bond-free surface and unique physics, promising their potentials for post-Moore's law computing. In this talk, I will describe our efforts towards low-power computing and bioinspired in-sensor computing with 2D semiconductors.

Ultrathin 2D semiconductors provide potential for downward scaling to nanoscale and low-power transistors. However, their dangling bond–free surface makes it extremely difficult to deposit gate dielectrics with high-quality interface in metal-oxide-semiconductor (MOS) field-effect transistors (FETs). We demonstrate a low-temperature process to transfer metal gate to 2D MoS_2 for high-quality interface. The high–barrier height Pt-MoS_2 Schottky junction replaces the commonly used MOS capacitor and eliminates the use of gate dielectrics, exhibiting sub-1 V operation voltage and a subthreshold slope close to thermal limit (60 mV/dec) and enabling logic functions in a single transistor with small footprint. [1]

The number of nodes typically used in sensory networks is growing rapidly, leading to large amounts of redundant data being exchanged between sensory terminals and computation units. To efficiently process such large amounts of data, it is necessary to develop approaches to computing that operate close to or inside sensory networks, and that can reduce the redundant data movement between sensing and processing units. [2] We demonstrate bioinspired in-sensor vision adaptation sensors that are based on MoS_2 phototransistors and exhibit time-varying activation and inhibition characteristics. The approach offers in-sensor visual adaptation with highly localized and dynamic modulation of photosensitivity under different lighting conditions at the pixel level, creating an effective perception range of up to 199 dB and showing both scotopic and photopic adaptation. [3]

[1] **Science Advances,** 2021, 7: eabf8744.
[2] **Nature Electronics,** 2020, 3, 664-671.
[3] **Nature Electronics,** 2022, 5, 84-91.

Dr. Yang Chai is an Assistant Dean of Faculty of Applied Science and Textile of the Hong Kong Polytechnic University, Vice President of Physical Society of Hong Kong, a member of The Hong Kong Young Academy of Sciences, an IEEE Distinguished Lecturer since 2016, and was the Chair of IEEE ED/SSC Hong Kong Chapter (2017-2019). He is a recipient of RGC Early Career Award in 2014, the Semiconductor Science and Technology Early Career Research Award in 2017, PolyU FAST Faculty Award in Research and Scholar Activities in 2018/2019, Young Scientist Award of ICON-2DMAT in 2019, PolyU President's Award in Research and Scholar Activities in 2019/2020, NR45 Young Innovators Award in 2021, and Young Scientist of World Laureate Forum in 2021. His current research interest mainly focuses on emerging electronic devices.

High-performance low-dimensional transistors based on ultra-thin body channel materials

Xin Wang[a], Yanqing Wu[a,b]

[a] Wuhan National High Magnetic Field Center and School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China.

[b] School of Integrated Circuits, Peking University, Beijing 100871, China.

yqwu@pku.edu.cn

Short channel effects influence silicon-based devices performance with continuous scaling. Atomically thin two-dimensional, such as transition metal dichalcogenides semiconductors, have potential to achieve the ultimate CMOS scaling. Monolayer transition metal dichalcogenides based on CVD grown, such as WSe_2 and MoS_2, are easily obtained with high mobility theoretically. However, lots of TMD devices suffered from high contact resistance and poor on-state current density in fact. Significant efforts have been made to improve the performance of planar TMD channel devices. Herein, we resolve these challenges by (i) synthesizing high-quality multilayer WSe_2 by molten-salt-assisted chemical vapor deposition with higher mobility and lower contact resistance than monolayer [1], (ii) vertical stacking channel with monolayer MoS_2 material and we have demonstrated the 2-monolayer-MoS_2-stacked nanosheets with a high on current 400 μA/μm at V_{ds} = 1 V and low contact resistance of 0.77 kΩ•μm [2]. Furthermore, the monolithic integration potential is proved by statistics of hundreds of devices fabricated on large-scale CVD MoS_2. And this facile synthesis of high-quality multilayer WSe_2 also provides a pathway for future high performance devices.

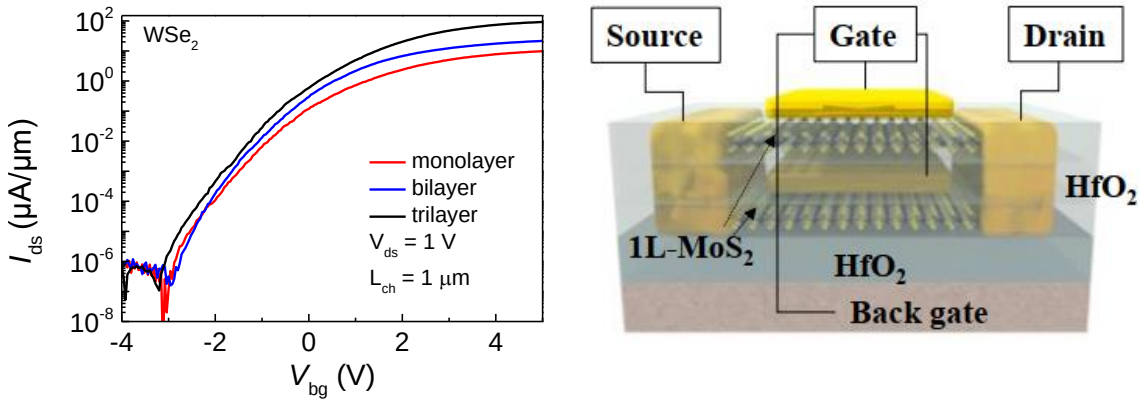

Fig 1. The layer-dependent transfer characteristics of WSe_2 transistors(left) and schematics of the 2-stacked MoS_2 nanosheets device(right).

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[2] Xiong, Xiong et al., IEEE IEDM, 2021, 7.5.1.

Towards chirality control of graphene nanoribbons embedded in hexagonal boron nitride

Haomin Wang [a, b, c]

[a] *State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai, P. R. China*
[b] *Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing, P. R. China*
[c] *CAS Center for Excellence in Superconducting Electronics (CENSE), Shanghai, P. R. China.*
hmwang@mail.sim.ac.cn

The integrated in-plane growth of graphene nanoribbons (GNRs) and hexagonal boron nitride (*h*-BN) could provide a promising route to achieve integrated circuitry of atomic thickness.[1] However, fabrication of edge-specific GNRs in the lattice of *h*-BN still remains a significant challenge. Here we developed a two-step growth method and successfully achieved sub-5-nm-wide zigzag and armchair GNRs embedded in *h*-BN. Further transport measurements reveal that the sub-7-nm-wide zigzag GNRs exhibit openings of the bandgap inversely proportional to their width, while narrow armchair GNRs exhibit some fluctuation in the bandgap-width relationship. An obvious conductance peak is observed in the transfer curves of 8- to 10-nm-wide zigzag GNRs, while it is absent in most armchair GNRs. Zigzag GNRs exhibit a small magnetic conductance, while armchair GNRs have much higher magnetic conductance values. This integrated lateral growth of edge-specific GNRs in *h*-BN provides a promising route to achieve intricate nanoscale circuits.

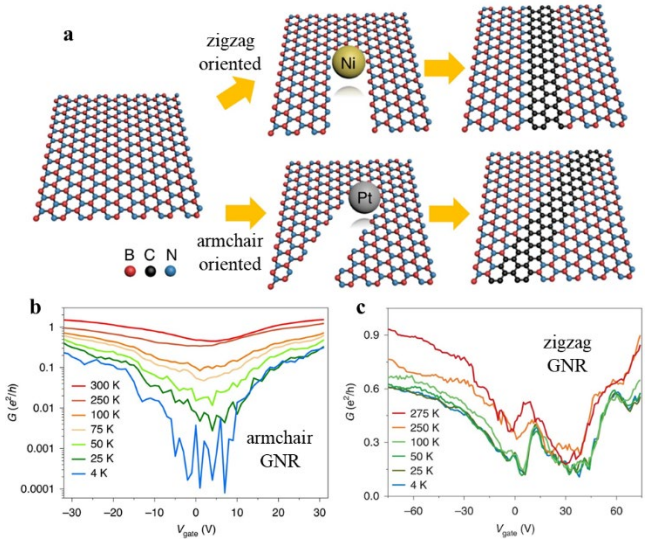

Fig.1 **a**, Synthetic strategy to orient GNRs with crystallographic edge orientations. **b**, **c**, The typical transfer curves of an ~5-nm-wide armchair GNR sample (**b**) and an ~8.9-nm-wide zigzag GNR sample (**c**) at different temperatures.

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Understanding nucleation theory to produce freestanding nanomembranes for artificial heterostructures

Sang-Hoon Bae

Department of Mechanical Engineering and Materials Science, Institute of Materials Science and Engineering

* Email: sbae22@wustl.edu

Abstract:
The electronics is an essential tool to power our homes, illuminate our lives, help our healthcare, connect all people, and even explore space. Electronics are everywhere. While extending the range of potential applications towards future electronics, we have faced with serious fundamental limitations in using the conventional electronics. One of these most prevalent limitations is the conventional electronics has a serious mechanical property mismatch with future applications as it has been developed on rigid wafers. Thus, an alternative approach has been required to minimize mismatch of mechanical property between the electronics and future applications.
In this seminar, I will talk about our team's effort to address the aforementioned challenge by producing freestanding nanomembranes. As the freestanding materials have extremely low stiffness, we expect to realize future electronics with minimal mechanical mismatch. First of all, using graphene's information transparency, we succeeded in growing single crystals on van der Waals-coated substrates. Unlike the conventional epitaxial growth on covalent-terminated substrates, an epitaxial growth on van der Waals surface seems to be challenging. That is mainly because of increased critical Gibbs free energy, suppressing nucleation rate on van der Waals surface. We realized utilizing remote interaction through 2D can be a source to suppress the Gibbs free energy. In addition, as the interface binding energy was attenuated due to van der Waals bonding, we were able to selectively exfoliate the grown single crystals from the substrates, producing freestanding single-crystalline materials. As this approach is universal, various freestanding materials were realized at large-scale so that new heterostructures can be discovered where new physical coupling and device architectures are realized [1,2].

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2. S. Bae, et al, "Integration of bulk materials with two-dimensional materials for physical coupling and applications", ***Nature Materials*** 18, 550 (2019)

Transparent Conducting Films Based on Carbon Nanotubes: Rational Design Towards the Theoretical Limit

Daniil A. Ilatovskii [a], Evgeniia P. Gilshtein [b], Olga E. Glukhova [c] and Albert G. Nasibulin [a,d]

[a] *Skolkovo Institute of Science and Technology, Nobel Str. 3, Moscow, Russian Federation*

[b] *Empa-Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, Dübendorf, 8600 Switzerland*

[c] *Saratov State University, Astrakhanskaya Str. 83, Saratov, Russian Federation*

[d] *Aalto University, FI-00076, Espoo, Finland*

a.nasibulin@skoltech.ru

Electrically conducting thin-film materials possessing high transparency are essential components for many optoelectronic devices. The advancement in the transparent conductor applications requires a replacement of indium tin oxide (ITO), one of the key materials in electronics. Despite being the most commonly used transparent conductive material, ITO as well as other metal oxides have several drawbacks, including limited mechanical flexibility, high refractive index and haze, limited chemical stability, and depleted raw material supply. Single-walled carbon nanotubes (SWCNTs) are one of the most promising alternative material platforms considered for transparent conducting films (TCFs) due to their excellent optoelectronic properties and unique mechanical flexibility and stretchability. Here, we analyze the latest achievements in the optoelectronic performance of TCFs based on SWCNTs. We also describe the roadmap for further research and development of the transparent conductors employing “rational design”, which breaks the deadlock for the TCFs obtained close to the theoretically limited performance.

Acknowledgements: A.G.N. acknowledges Russian Foundation of Basic Research project no. 20-03-00804. D.A.I. and O.E.G. acknowledge the Russian Science Foundation (project No. 21-19-00226). The work was supported by the Council on grants (number НШ-1330.2022.1.3).

An electron microscopy analysis of challenges of carbon nanotube transistors: an electron microscopy viewpoint

Chuanhong Jin

State Key Laboratory of Silicon Materials, School of Materials Science and Engineering, Zhejiang University, Hangzhou, China

chhjin@zju.edu.cn

Carbon nanotube based electronic technology has achieved tremendous breakthroughs in past two decades, while challenges still remain in different aspects, including the material preparation, optimization of CNT transistor and COMS techniques and the fabrication of large-scale CNT based circuits. These challenges may further delay the industrialization of CNT based ICs. In this work, we will report some of our early results on analyzing the microscopic structures of state-of-the-art CNT array based transistors via advanced electron microscopy and spectroscopy. Intrinsic and processing dependent imperfections of the key components of CNFETs are partly revealed like the misalignment and aggregation of CNTs in the channel, fluctuations in contact geometry (facets, grain size, strain distribution and coverage) in metal contacts and the conformity in high-k dielectrics. These results indicate further improvements are certainly needed to optimize the CNT array transistors.

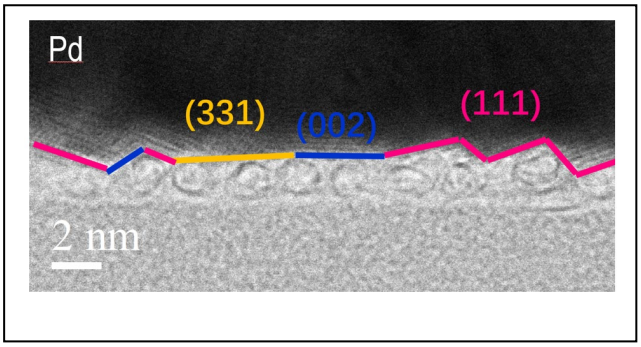

Fig 1. A typical HRTEM micrograph showing the Pd-CNT array interface

Ultrafast 2D nonvolatile memory operation provided by the strong sh ort-Time dielectric breakdown strength of *h*-BN

Nagashio Kosuke
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656 JAPAN
nagashio@material.t.u-tokyo.ac.jp

2D heterostructures have been extensively investigated as next-generation non-volatile memory (NVM) devices. In the last decade, drastic performance improvements and further advanced functionalities have been demonstrated. However, this progress is not sufficiently supported by the understanding of their operations, obscuring the material and device structure design policy. Here, detailed operation mechanisms are elucidated by exploiting the floating gate voltage (V_{FG}) trajectory measurements [1,2]. Systematic comparisons of $MoTe_2$, WSe_2, and MoS_2 channel devices revealed that the tunneling behavior between the channel and FG is controlled by three kinds of current-limiting paths, *i.e.,* tunneling barrier, 2D/metal contact, and *pn* junction in the channel. Based on the understanding of the memory operation mechanism through the V_{FG} trajectory measurment, we propose the best all 2D NVM device structure with a direct tunneling path between source/drain electrodes and floating gate for ultrafast memory operation. Indeed, a 50 ns program/erase operation is successfully achieved [3]. Moreover, we examined the dielectric breakdown strength (E_{BD}) of *h*-BN under short voltage pulses for the origin for this ultrafast operation, because a high dielectric breakdown strength allows a large tunneling current. Surprisingly, an E_{BD} = 26.1 MV/cm for *h*-BN is realized under short voltage pulses, largely exceeding the E_{BD} = ~12 MV/cm from the DC measurement. This suggests that the high E_{BD} of *h*-BN can be the physical origin of the ultrafast operations. In this talk, I would like to discuss the future perspective of 2D NVM application.

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Small Molecular Additives to Suppress Bundling in Dimension-Limited Self-Alignment Method for High-Density Aligned CNT Arrays

Tzu-Ang Chao[a,b], Gregory Pitner[c], H.-S. Philip Wong[a], Han Wang[c], Wen-Hao Chang[bd]
[a]*Corporate Research, Taiwan Semiconductor Manufacturing Company, Hsinchu, Taiwan*
[b]*Department of Electrophysics, National Yang Ming Chiao Tung University, Hsinchu, Taiwan*
[c]*Corporate Research, Taiwan Semiconductor Manufacturing Company, San Jose, USA*
[d]*Research Center for Applied Sciences, Academia Sinica, Taipei, Taiwan*
Email: tachao@tsmc.com, hanwang@tsmc.com , whchang@nycu.edu.tw

Semiconducting single-walled carbon nanotube (CNT) is a candidate channel material for advanced logic technology due to its ultra-thin cylindrical geometry and high mobility. Recently there have been several fundamental advances demonstrated towards high-performance and scaled CNT transistors [1-5]. However, the most challenging obstacle is still the relatively low quality of the aligned CNT arrays. In this talk, we will describe the desired qualities of a CNT channel for advanced logic application, including a uniform pitch ~4 nm (corresponding to 250 CNT/μm) and minimal CNT bundling. We studied the properties of densely aligned CNT arrays formed by a state-of-the-art assembly method called dimension-limited self-alignment (DLSA) [3]. In a DLSA assembly system, CNTs are first wrapped by Polycarbazole (PCz) polymers in solvent, then assembled at a binary-liquid interface between trichloroethane and 2-butene-1,4-diol due to interactions with Nitrogen atoms in PCz, and finally deposited on a substrate [3]. We propose a mechanism that explains the observed bundles in the DLSA assembled CNT array, whereby the CNT-CNT van der Waals attractions at the binary-liquid interface plays a key role. To reduce the van der Waals attractions between the CNTs, a novel molecular additive is developed, which delivers >50% reduction in CNT bundling as confirmed by statistical cross-section TEM analysis. This finding suggests new pathways towards achieving bundle-free high-density CNT array using optimized molecular additives for DLSA assembly of CNT.

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Parallel Symposia **LOW DIMENSIONAL ELECTRONICS @ Chemistry Building # 330102**

Thursday, JUNE 23rd, 2022

		Chair: Tae-Woo Lee (Seoul National University)
14:30-15:00	P-Lo-I9	**Jana Zaumseil** (Heidelberg University, Germany) *Charge Transport in Networks of Semiconducting Single-Walled Carbon Nanotubes*
15:00-15:30	P-Lo-I10	**Dmitri Golberg** (Queensland University of Technology, Australia) *In-situ transmission electron microscopy studies of graphene and carbon nanotube properties*
15:30-15:40	Short break	
		Chair: Dmitri Golberg (Queensland University of Technology)
15:40-16:10	P-Lo-I11	**Shinpei Ogawa** (Mitsubishi Electric Corporation, Japan) *Graphene photogated diodes for high-performance infrared imaging*
16:10-16:40	P-Lo-I12	**Gregory Pitner** (Taiwan Semiconductor Manufacturing Company, USA) *Carbon Nanotube Transistors: Recent progress towards applications in highly-scaled and high-performance CMOS logic*
16:40-17:00	P-Lo-I13	**Harri Lipsanen** (Aalto University, Finland) *Multilayer MoTe2 Field Effect Transistor under Extreme Operating Conditions*

Friday, JUNE 24th, 2022

		Chair: Woojong Yu (Sungkyunkwan University)
13:15-13:35	P-Lo-C3	**Arindam Bala** (Sungkyunkwan University, Korea) *Highly Responsive Photonic Detection with Uniform Thin-film Transistors Array Using Large-Area Bilayer WS2*
13:35-14:05	P-Lo-I14	**Jeff Blackburn** (National Renewable Energy Laboratory, USA) *Energy Harvesting and Low-Power Electronic Devices with Semiconducting Single-Walled Carbon Nanotubes*
14:05-14:25	Short break	
		Chair: Jana Zaumseil (Heidelberg university)
14:25-14:45	P-Lo-C4	**Patrick Edwards (**Physical Sciences Laboratories, USA) *Electrical Measurement of Water Assisted Ion Desorption and Solvation on Isolated Carbon Nanotubes*
14:45-15:05	P-Lo-C5	**Vikram Deshpande** (University of Utah, USA) *Vernier Spectrum and Valley Polarization Control in Carbon Nanotube Quantum Dots*

Charge Transport in Networks of Semiconducting Single-Walled Carbon Nanotubes

Jana Zaumseil
Institute for Physical Chemistry, Heidelberg University
Im Neuenheimer Feld 253, D-69120 Heidelberg, Germany
zaumseil@uni-heidelberg.de

Fast charge transport in random networks of semiconducting single-walled carbon nanotubes (SWNTs) is the basis for their application in many electronic devices, specifically in field-effect transistors (FETs) and electronic circuits. The recent advances in selective growth, purification and sorting of semiconducting and even monochiral SWNTs have enabled FETs with high carrier mobilities and on/off current ratios that are suitable for a wide range of applications. Controlled n- and p-doping even enables the fabrication of complementary and low power circuits [1]. To further improve device performance, it is important to understand the interplay of various network parameters such as nanotube density, length, diameter distribution [2], carrier density, intentional (e.g., luminescent) and unintentional defects [3], dielectric environment etc. and their impact on the macroscopic charge transport properties [4]. Here, I will give an overview of our recent progress on understanding and improving charge transport in networks of polymer-sorted, solution-processed semiconducting SWNTs.

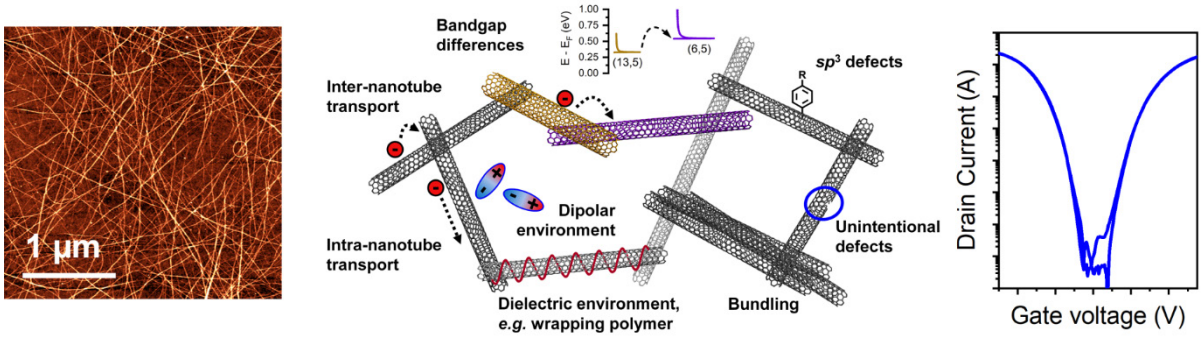

Fig 1. Random network of SWNTs and schematic of various factors influencing charges transport as reflected in transfer characteristics of an FET [4].

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In-situ transmission electron microscopy studies of graphene and carbon nanotube properties

Dmitri V. Golberg
Queensland University of Technology (QUT)
2 George str, Brisbane, QLD 4000, Australia
dmitry.golberg@qut.edu.au

Using advanced methods on in-situ high resolution transmission electron microscopy (TEM) for property analysis of graphene and carbon nanotubes is presented. Delicate experiments inside a microscope column while utilizing diverse in situ TEM holders, e.g., those providing the information in regard of electrical and mechanical properties of carbon nanostructures, are shown. Intra-diffusion kinetics at the metal-electrode/carbon interfaces, shaping graphene edges [1], telescoping and thinning [2] of carbon nanotubes, and transforming metallic carbon nanotubes to ultrashort semiconducting channels of only 2.8 nm long [3] are illustrated.

This work was supported through the Australian Research Council (ARC) Laureate Project FL160100089. The author is particularly grateful to many former group members and colleagues, i.e., Daiming Tang, Mingsheng Wang, Xianlong Wei, Xin Zhou, Ovidiu Cretu, Dmitry Kvashnin, and Pavel Sorokin, for their key contributions to the in-situ TEM projects over the years.

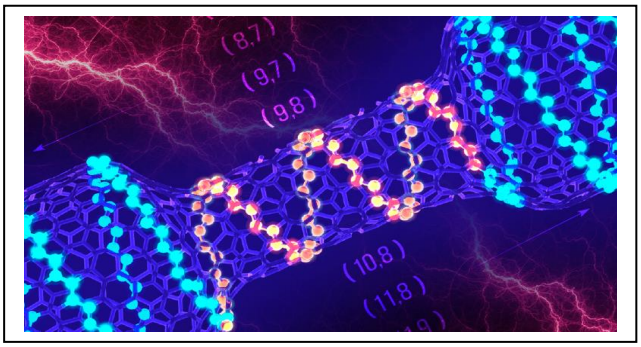

Fig 1. Artistic view of an ultrashort semiconducting channel within a metallic carbon nanotube created through thermomechanical alternation of nanotube helicity in TEM [3].

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Graphene photogated diodes for high-performance infrared imaging

Shinpei Ogawa, Masaaki Shimatani, and Shoichiro Fukushima
Advanced Technology R&D Center, Mitsubishi Electric Corporation,
8-1-1 Tsukaguchi-Honmachi, Amagasaki, Hyogo 661-8661, Japan
Ogawa.Shimpei@eb.MitsubishiElectric.co.jp

Graphene photogated diodes (GPDs) have been developed for high-performance infrared imaging[1, 2]. Photogating is a unique responsivity enhancement method of graphene-based photodetectors, which cannot be achieved by a conventional technology, owing to the high carrier mobility and atomic thickness of graphene. We have demonstrated ultra-high responsivity graphene field effect transistor (GFET)-based photodetectors using the photogating method in the visible and near-IR[3, 4], middle-[5] or long-wavelength IR[6] (MWIR or LWIR) range. However, GFETs produce a large dark current and require three port operation. These disadvantages limit IR photodetector performance. To address this challenge, we have developed GPDs operating in the MWIR range. As shown in Fig. 1(a), GPDs have a diode structure with two ports and a direct contact region between graphene and InSb, where the Schottky barrier is formed and blocks dark current. Simultaneously, the photogating effect is maintained by the SiO_2 and graphene region. Fig. 1(b) shows the MWIR photoresponse of the developed GPD. The dark current was reduced to less than $1/10^7$ compared with GFET-based photodetectors and maintained a nearly constant high responsivity. These findings can contribute to the development of high-performance graphene-based IR image sensors.

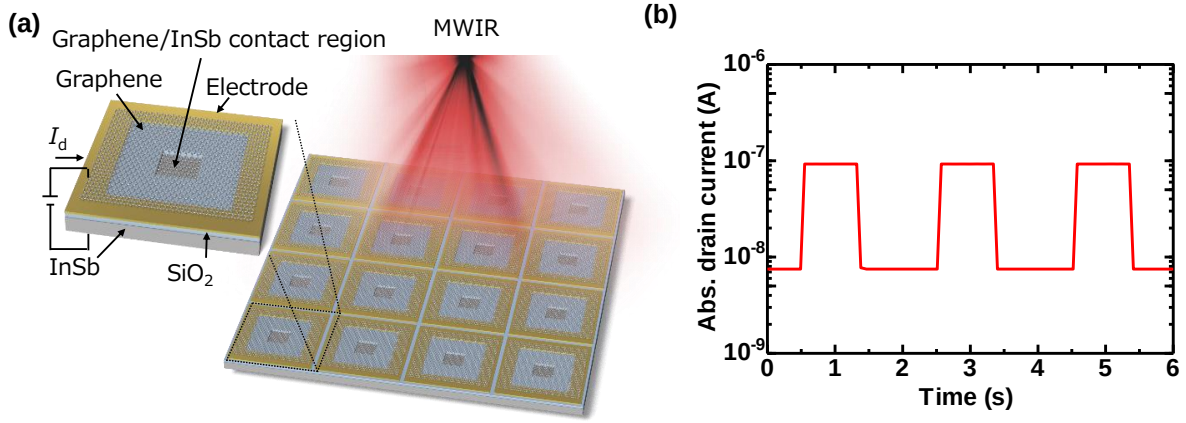

Fig 1. (a) Schematic of GPDs and (b) MWIR photoresponse.

Acknowledgements
This work was partially supported by the Innovative Science and Technology Initiative for Security Grant Number: JPJ004596, ATLA, Japan.

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Carbon Nanotube Transistors: Recent progress towards applications in highly-scaled and high-performance CMOS logic

Gregory Pitner[1], Sheng-Kai Su[2], Tzu-Ang Chao[2], Nate Safron[1], Edward Chen[2], Matthias Passlack[1], H.-S. Philip Wong[2], Han Wang[2], Iuliana Radu[2]

[1]Corporate Research, Taiwan Semiconductor Manufacturing Company, San Jose, CA, USA

[2]Corporate Research, Taiwan Semiconductor Manufacturing Company, Hsinchu, Taiwan

Email: gpitner@tsmc.com

Three decades of fundamental research on Carbon Nanotube (CNT) materials and devices have generated tremendous progress towards useful applications. In this talk, we will first introduce the motivations and review the challenges towards utilizing semiconducting single-walled CNTs as a channel material in highly scaled and high-performance CMOS transistors [1-3]. We will summarize recent experimental advances on CNT transistors by our team and collaborators including: (1) the lowest reported CNT contact resistance of 6.5 kΩ per CNT down to 10 nm contact length [4], (2) a method to deposit sub-3 nm high-capacitance gate dielectrics on CNT for excellent electrostatics down to 15 nm gate length [5-6], and (3) the first systematic study of band-to-band tunneling leakage in CNT MOSFETs which gives insight into the desired CNT bandgap for energy efficiency [7]. We will outline from a transistor perspective the remaining challenges of CNT materials assembly and controlled CNT doping to encourage research directions in the scientific community.

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Multilayer $MoTe_2$ Field Effect Transistor under Extreme Operating Conditions

F. Ahmed[a], A. M. Shafi[a], D. M. A. Mackenzie[a], M. A. Qureshi[b], H. A. Fernandez[a], H. H. Yoon[a], M. G. Uddin[a], M. Kuittinen[b], Z. Sun[a], and Harri Lipsanen[a]

[a] *Department of Electronics and Nanoengineering, Aalto University, P.O. Box 13500, Aalto FI-00076, Finland*

[b] *Institute of Photonics, University of Eastern Finland, P.O. Box 111, Joensuu FI-80101, Finland*

harri.lipsanen@aalto.fi

The two-dimensional (2D) materials-based solid-state devices are considered as the leading contenders for post-silicon electronics, optoelectronics, and memory applications. The functional 2D devices are likely subjected to large thermal stress induced by high packing density in miniaturized integrated circuits along with low thermal conductivity and small heat capacity of 2D materials. In results, the large thermal stress may induce irreversible structural changes in 2D materials and affect the device performance. Therefore, in this study, we are systematically investigating the electrical and structural properties of multilayer $MoTe_2$ based field-effect transistor to high ambient temperatures (up to 673 K). We identified the optimal annealing temperature of around 500 – 525 K for the multilayer $MoTe_2$ devices, which coincides with tellurium atom dissociation temperature, suggesting permanent changes in $MoTe_2$ afterwards. Moreover, $MoTe_2$ devices surprisingly showed vanishing gate control to the degenerately *p*-doped characteristics at an increasing temperature to 600 K, which is caused by near range hopping transport in the defective $MoTe_2$ channel. The evolving *p*-type characteristics are caused by the thermally triggered oxidation of $MoTe_2$ as confirmed by XPS analysis. These results will be helpful in designing practical and durable $MoTe_2$ devices.

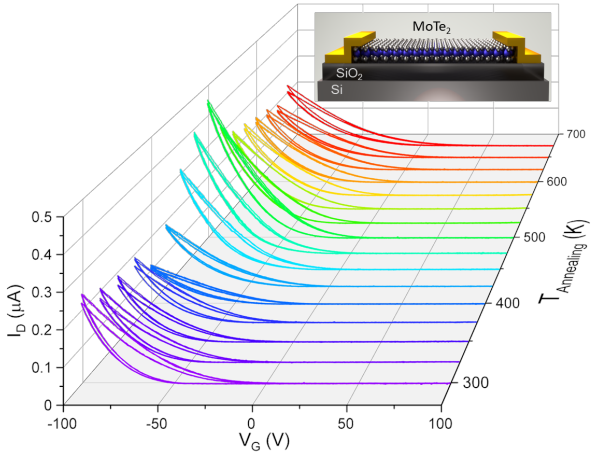

Fig.1. The measured hysteresis plots at room temperature at V_D = 1 V after annealing to 673 K with the step of 25 K. Inset is the schematic of $MoTe_2$ backgated device on Si/SiO_2 substrate.

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Highly Responsive Photonic Detection with Uniform Thin-film Transistors Array Using Large-Area Bilayer WS_2

*Arindam Bala, Na Liu, Muhammad Naqi, Haewon Cho, Anamika Sen and Sunkook Kim**

School of Advanced Materials Science and Engineering, Sungkyunkwan University, Suwon, 16419, Republic of Korea

Email: intel0616@gmail.com

Among transition metal dichalcogenides, WS_2 has been considered as promising photon absorption semiconductors for future image sensing devices due to its tailoring ability of bandgap, ultrafast photoresponsive behavior, and stable electrical characteristics. Here, we demonstrate a highly responsive photonic detection of large area grown bilayer WS_2 semiconductor. The WS_2 film (4-inch diameter wafer) is directly grown on a SiO_2/Si substrate via a two-step process. The fabricated WS_2 thin-film transistors (TFTs) exhibit field-effect mobility of 4 to 10 cm^2/V s and an average on/off current ratio of 2×10^6. The WS_2 TFTs exhibited a high photoresponsivity of 1821 A/W under blue light (λ = 405 nm) illumination at 0.84 mW/cm^2 power level, which is attributed to the photogating effect in response to the trap states in the bandgap according to our model. In addition, a 7 × 6 phototransistors array is fabricated, which exhibits uniform photodetection properties in terms of responsivity and detectivity. The linear and stable photodetection of large area WS_2 phototransistor paving a way towards next-generation large-scale optoelectronic applications.

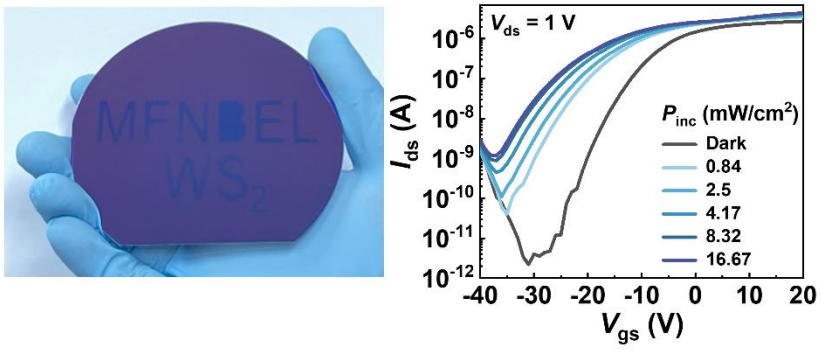

Fig.1 Schematics for wafer scale grown WS_2 with patterning and photo response of WS_2TFT under blue light illumination.

Energy Harvesting and Low-Power Electronic Devices with Semiconducting Single-Walled Carbon Nanotubes

Corresponding Author: *Dr. Jeffrey L. Blackburn*
National Renewable Energy Laboratory
jeffrey.blackburn@nrel.gov
15013 Denver West Parkway
Golden, CO 80401-3305
USA

National Renewable Energy Laboratory, Golden, CO 80401

Low-dimensional semiconductors provide a rich tapestry of tunable optical and electrical properties for a wide variety of applications. Semiconducting single-walled carbon nanotubes (s-SWCNTs) have shown tremendous potential in applications ranging from digital logic, biological imaging, quantum information processing, photovoltaics, and thermoelectric energy harvesting. Energy harvesting and transduction applications rely critically upon the creation of tailored charge carrier densities and interfaces with appropriate band alignments that enable the movement of energetic species (excitons, electrons, holes) in specified directions.

In this talk, I will discuss our recent efforts at constructing energy harvesting and low-power electronic devices that incorporate s-SWCNTs with tuned carrier densities and rationally designed heterostructures between s-SWCNTs and other low-dimensional semiconductors. These devices enable energy harvesting across multiple regions of the electro-magnetic spectrum,[1,2] photon detection at exceptionally low power consumption,[3] and transduction of circularly polarized photons into photocurrent with efficiencies that depend on the handedness of the incident photons.[4] A combination of spectroscopy, transport measurements, and three-terminal (photo)transistor device studies provides a picture of the working mechanisms for the systems. Several potential application spaces will be discussed, including photovoltaics, novel photodetectors, and thermoelectric energy harvesting devices.

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Electrical Measurement of Water Assisted Ion Desorption and Solvation on Isolated Carbon Nanotubes

Patrick J. Edwards [a], Bo Wang [b], Stephen B. Cronin [c], and Adam Bushmaker [a]
[a] *Physical Sciences Laboratories, The Aerospace Corporation, El Segundo, California 90245, United States.*
[b] *Department of Physics, The University of Southern California, Los Angeles, California 90089, United States.*
[c] *Department of Electrical Engineering, The University of Southern California, Los Angeles, California 90089, United States.*
Patrick.J.Edwards@aero.org

With continued reduction in the feature size of device structures we are quickly approaching the one-dimensional limit of electrical conduction. In this regime it becomes increasingly important to study the effects of individual dopants and defects on device performance. Recent studies on the electrical properties of suspended carbon nanotube field-effect transistors (CNT-FETs) have revealed extreme sensitivity in device conductivity in the presence of individual gaseous ions adsorbed at the nanotube surface. We will present an investigation on the mean residence time of gaseous ions adsorbed on the surface CNT-FETs with and without native surface water layers that exist in atmospheric conditions. Devices dehydrated by various methods were all found to have substantially higher mean ion residence times (Fig 1 [1]). We propose that native water molecules in ambient conditions provide a reduction pathway for incoming gaseous ions, yielding Hydronium ions (H_3O^+). We characterize the interaction between these ions with the CNT-FET surface via large switching events in device conduction and compare to measurements taken on desiccated devices.

Vernier Spectrum and Valley Polarization Control in Carbon Nanotube Quantum Dots

Vikram V Deshpande
Department of Physics & Astronomy, University of Utah, Salt Lake City UT, 84112 USA
vdesh@physics.utah.edu

Dirac cones can tilt or warp due to spin-orbit or lattice interaction resulting in asymmetric velocities for left- and right-moving electrons. In carbon nanotubes, this effect has manifested in a secondary quantum interference [1, 2] on top of the Fabry-Perot interference. In finite-sized systems such as quantum dots, this effect is predicted [3] to result in unequally spaced energy levels for left/right movers or K/K' valley electrons leading to accidental degeneracies and a Vernier spectrum. In this work, we present the Vernier-like spectrum seen in Coulomb blockade measurements of ultraclean suspended carbon nanotubes. Four-fold shell filling on a slowly oscillating background conductance versus gate voltage is seen to be interrupted periodically to add two additional electrons. We present a theoretical model to describe such behavior in the conductance of finite-sized nanotubes that lifts the four-fold degeneracy and gives rise to the Vernier-like spectrum. The model also shows that valley-polarized energy levels are available at specific gate voltages, and the degree of polarization can be tuned by gate voltage. Our work showcases the continued surprises revealed by quantum transport in ultraclean carbon nanotubes.

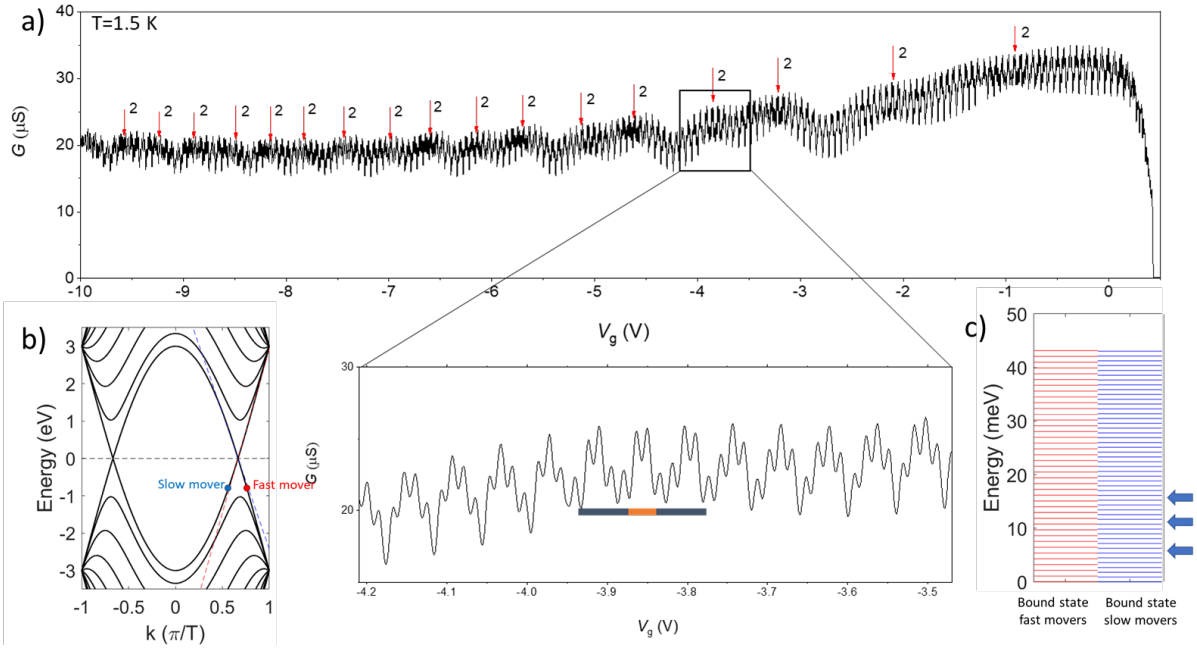

Fig 1. Experimental manifestation of the Vernier effect in ultraclean carbon nanotubes. (a) Conductance (G) of a ~2 μm long carbon nanotube quantum dot plotted versus gate voltage (V_g). Arrows indicate the insertion of two additional electrons periodically. (Inset) Blow up of rectangle. (b) Due to asymmetry in the dispersion, there are slow- and fast-moving states near the Fermi level. (c) Unequally spaced fast- and slow-moving bound states create a Vernier scale.

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The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

Parallel Symposia Program & Abstract

Theory

Parallel Symposia **THEORY @ Chemistry Building # 330110**

Monday, JUNE 20th, 2022

		Chair: Young Woo Son (Korea Inst. For Advanced Study)
14:30-15:00	P-Th-I1	**Christophe Bichara** (CNRS and Aix-Marseille University, France) *Swinging interfaces of growing carbon nanotubes*
15:00-15:30	P-Th-I2	**Qinghong Yuan** (East China Normal University, China) *Structure and property engineering of two-dimensional carbon nitride materials*
15:30-15:40	Short break	
		Chair: Sergei Tretiak (Los Alamos National Laboratory)
15:40-16:10	P-Th-I3	**Jeil Jung** (University of Seoul, Korea) *Electronic structure of lattice relaxed alternating twist tNG multilayer graphene*
16:10-16:40	P-Th-I4	**Mikito Koshino** (Osaka University, Japan) *Topological quasicrystals in twisted 2D systems*
16:40-17:00	P-Th-C1	**Youngkuk Kim** (Sungkyunkwan University, Korea) *Higher-Order Topological Corner State Tunneling in Twisted Bilayer Graphene*

Tuesday, JUNE 21st, 2022

		Chair: Feng Ding (IBS UNIST)
14:30-15:00	P-Th-I5	**Hyoung Joon Choi** (Yonsei University, Korea) *Electronic structures and interactions in graphene moiré superlattices*
15:00-15:30	P-Th-I6	**Ting Cao** (University of Washington, USA) *Tunable Magnetism and Excitonic Effects in 2D Magnetic Semiconductors*
15:30-15:40	Short break	
		Chair: James Elliott (University of Cambridge)
15:40-16:10	P-Th-I7	**Alister Page** (University of Newcastle, Australia) *Structure, Properties and Growth of 1D van der Waals Heterostructures - Computational Challenges*
16:10-16:30	P-Th-C2	**Daniel Hedman** (IBS CMCM, Korea) *Atomistic simulations of carbon nanotube growth using machine learning force fields - from a clean Fe cluster to a fully grown tube*
16:30-16:50	P-Th-C3	**Tenta Tani** (Osaka University, Japan) *Topological edge and corner states and fractional corner charges in blue phosphorene*

Swinging interfaces of growing carbon nanotubes

Christophe Bichara

CINaM, CNRS and Aix-Marseille University, Marseille, France

Christophe.bichara@univ-mrs.fr

In classical crystal growth, the interaction of the growing object with its support and the energies of the different facets determine the growth mode and the resulting crystalline structures. The synthesis of carbon nanotubes by chemical vapor deposition poses somewhat similar yet more complex issues. The catalytic particle is both a support and a reactive interface with the growing tube, and many properties are altered because of the nanometric size of the objects.

In this context, we have identified different growth modes driven by the thermodynamic properties of the interface [1, 2] and developed a model of the interface [3], emphasizing the importance of the configurational entropy of the nanotube edge to stabilize chiral tubes and to account for the temperature dependence of tube helicity distributions. This simple model is pushed further to account for more general interface structures and kinetic Monte Carlo (KMC) simulations are developed [4] to study the growth mechanisms and kinetics, and analyze growth rates in relation with the chiral selectivity of the synthesis.

In this presentation we theoretically investigate new *in situ* measurements of individual CNT growth rates by homodyne polarization microscopy [5] with better temporal and statistical resolution than previous studies [6]. The growth kinetics are surprisingly complex and exhibit instabilities characterized by stochastic alternations of growth, etching, stops and sometimes restarts. These events occur with or without changes in the structure of the single-walled nanotube. We study the latter case, propose a simple modeling and KMC simulations, thus shedding new light on the role of the tube/catalyst interface dynamics for both thermodynamic and kinetic aspects of the growth.

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Structure and property engineering of two-dimensional carbon nitride materials

Qinghong Yuan[1]

[1] *State Key Laboratory of Precision Spectroscopy, School of Physics and Electronic Science, East China Normal University, 500 Dongchuan Road, Shanghai 200241, China*

qhyuan@phy.ecnu.edu.cn

Two-dimensional (2D) carbon nitrides have been attracting extensive attentions due to their potential applications in semiconductor devices, high-performance catalyst, lithium-ion batteries, supercapacitors, fuel cells, hydrogen storage materials, etc. However, the controllable synthesis of 2D carbon nitride or nitrogen-doped graphene (NG) has been challenging and the materials fabricated in experiments always has low N concentration and a mixture of N dopants. In this talk, we will discuss i) the most stable structures of 2D $C_{1-x}N_x$ with varying nitrogen concentration, [1] ii) the co-doping of both graphitic- and pyridinic- N in $C_{1-x}N_x$ and the optimum position of the doped N atoms, [2] iii) structure control of 2D $C_{1-x}N_x$ through C/N feedstocks, hydrogen pressure and temperatures. [1] Moreover, we will talk about the bandgap engineering of bilayer C_3N by controlling the stacking order or applying an external electric field. The significant bandgap change of bilayer C_3N was predicted by calculations and further confirmed by experimental observations. [3] This effective bandgap engineering of 2D-bilayer C_3N offers a new opportunity for high performance carbon-based electronics.

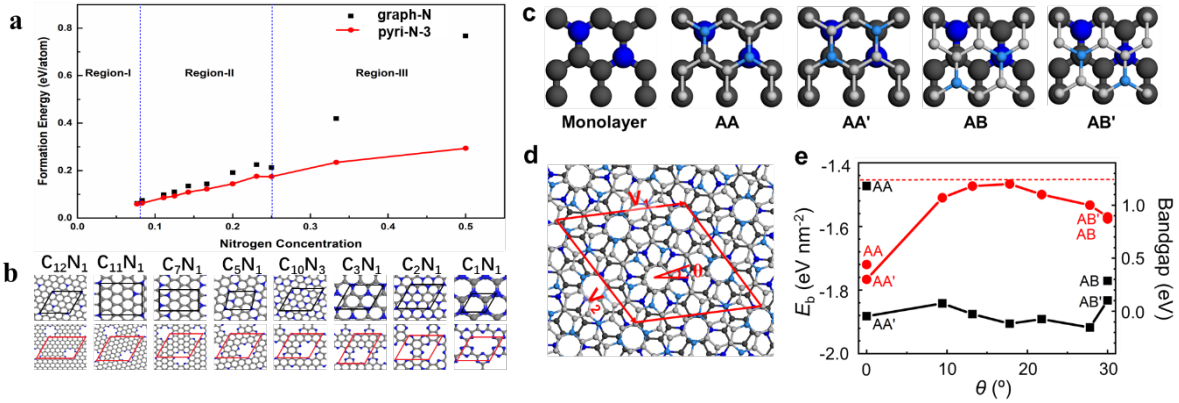

Fig 1. **a**, The formation energies at 0 K. **b**, optimized structures of the most stable $C_{1-x}N_x$ structures doped with graphitic or pyridinic N. **c**, Illustration of the C_3N monolayer and the C_3N bilayer with AA, AA', AB, AB' stacking. **d**, Schematic diagram of a C_3Nbilayer with a twist angle of θ, a commensurate unit cell (CUC) with θ=21.8°, where v_1 and v_2 are two vectors of the CUC with coprime indices (2, 1). **e**, Binding energies (black squares) and bandgaps (red circles) of bilayer C_3N as a function of the twist angle. The red dashed line shows the bandgap of monolayer C_3N and the arrows are provided as a guide to the eyes.

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Electronic structure of lattice relaxed alternating twist tNG multilayer graphene

Jeil Jung
Department of Physics, University of Seoul, Seoul 02504, Korea
Department of Smart Cities, University of Seoul, Seoul 02504, Korea
jeiljung@uos.ac.kr

Magic angle twisted bilayer and multilayer graphene has become a fruitful testbed for exploring the properties of moire superlattices and nearly flat bands that give rise to strong correlations. In this talk I will present a real-space atomistic approach to calculate the interdependent electronic and atomic structure of twisted bilayer and multilayer graphene where we attempt to progressively improve the accuracy of the models in both fronts. As concrete examples, we begin by showing how the Fermi velocity, interlayer tunneling and lattice relaxation influence the magic angle band structures in twisted bilayer graphene. We then expand our studies to multilayer alternating twist tNG systems to assess the evolution of the bands with larger layer number N. Due to the moire strains, we show how the lattice relaxation helps to stabilize a given interlayer stacking configuration and works towards the reduction of the magic angles with respect to rigid system's values. The range of twist angles giving rise to magic angle density of states maxima expand progressively from 0.05 degrees of t2G up to 0.2 in the limit of large N. Our work shows routine applicability of real space atomistic approaches for addressing the physics of twisted graphene systems involving multiple moire patterns.

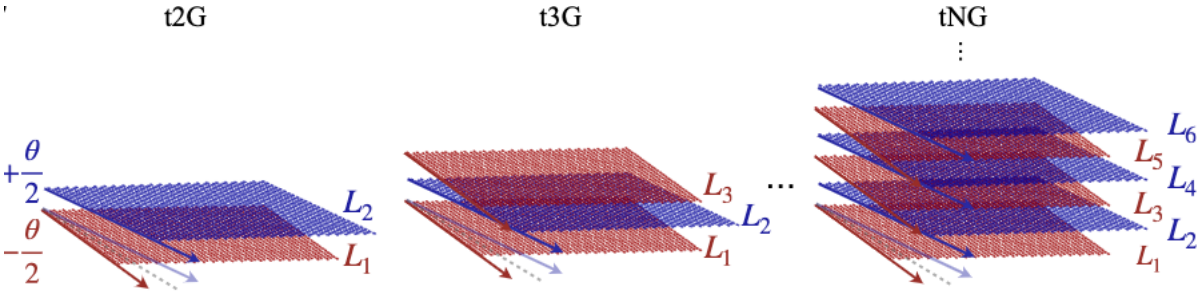

Fig 1. Schematic of alternating twist t2G, t3G, t6G multilayers and beyond numbered from bottom to top.

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Topological quasicrystals in twisted 2D systems

Mikito Koshino
Department of Physics, Osaka University,
Osaka 560-0043, Japan
koshino@phys.sci.osaka-u.ac.jp

When two atomic layers are overlaid with an arbitrary rotation angle, the periodicities of the individual layers do not generally match, and the entire system becomes quasiperiodic. A remarkable feature of these twisted 2D quasicrystals is that the electronic structure can be continuously modified by changing the twist angle or any deformations of the individual lattice structure. For instance, twisted bilayer graphene has a highly tunable band structure depending on the twist angle, ranging from the moiré flat bands in the small-angle regime to a 12-fold rotationally symmetric quasicrystal at 30 degree.
In this talk, we present our recent theoretical works on topological natures of such quasiperiodic twisted 2D systems, including twisted bilayer graphenes and also hBN/graphene/hBN trilayer system [1]. In particular, we show that the electronic spectrum plotted against the twist angle generally contains a number of fractal minigaps, where each gap can be characterized by a set of topological invariants associated with area of a quasi Brillouin zone. These quantum numbers can be expressed as second Chern numbers by considering a formal relationship between an adiabatic charge pumping under the interlayer slide and a topological nonlinear electromagnetic response in 4D band insulators. [2]

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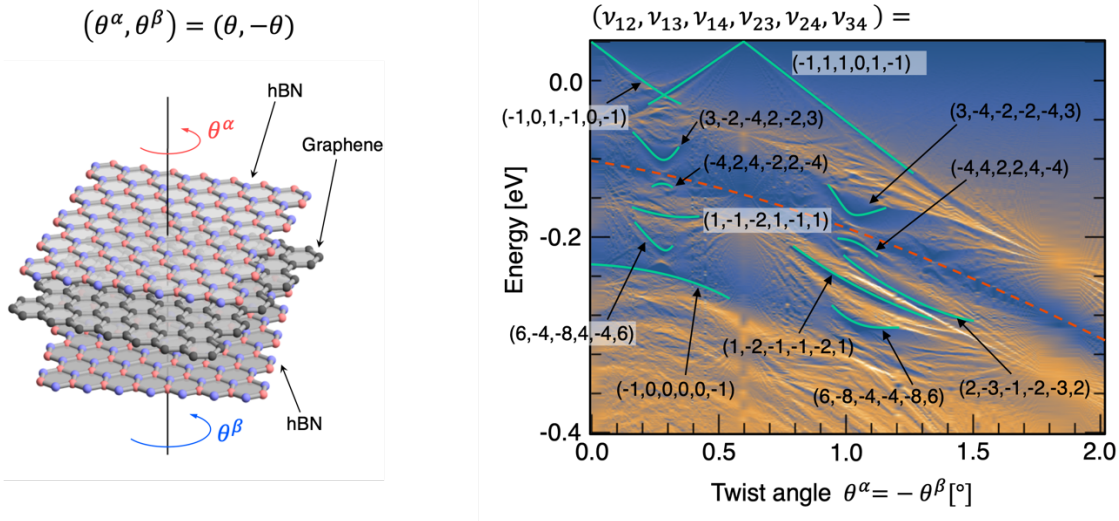

Fig. 1 (a) Structure of the hBN/graphene/hBN trilayer system. (b) Color map of the density of states of hBN/graphene/hBN system plotted against twist angle. Numbers in minigaps indicate topological invariants.

Higher-Order Topological Corner State Tunneling in Twisted Bilayer Graphene

Youngkuk Kim [a,b]

[a] *Department of Physics, Sungkyunkwan University, Suwon 16419, Republic of Korea*
[b] *Center for Integrated Nanostructure Physics (CINAP), Institute for Basic Science (IBS), Sungkyunkwan University, Suwon 16419, Republic of Korea.*
youngkuk@skku.edu

A higher-order topological insulator (HOTI) is a phase of matter characterized by the localized states at lower-dimensional boundaries. Here we show that twisted bilayer graphene can harbor a second-order topological insulating phase [1]. We then argue that the HOTI phase in twisted bilayer graphene can be experimentally identified by a novel quantum oscillation in quantum transport measurements [2], which originate from an instanton tunneling between topological corner states. Our results suggest a feasible route to distinguish the topologically trivial and nontrivial corner states.

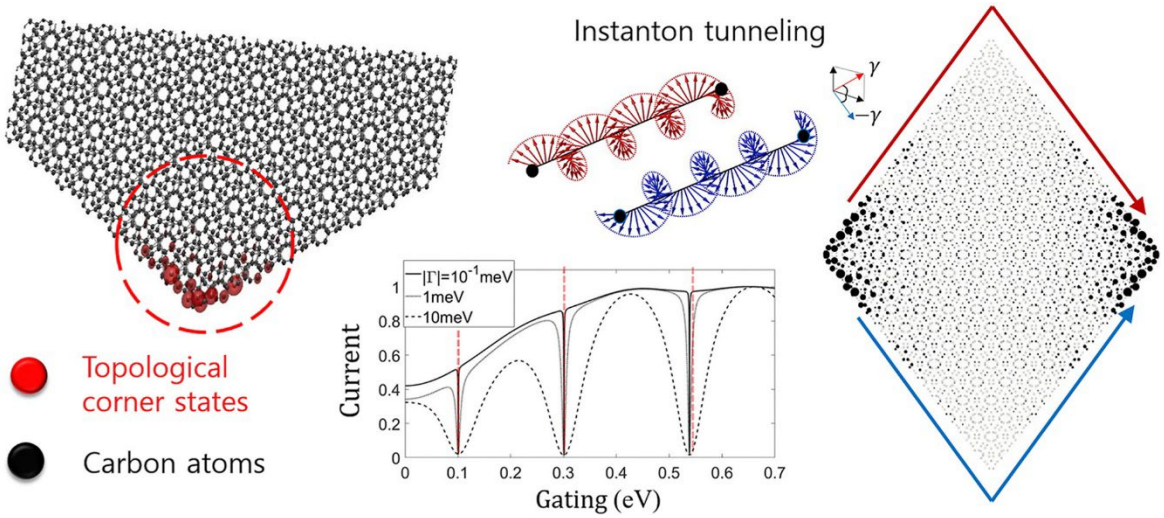

Fig.1 Schematic illustration of topological corner states of twisted bilayer graphene and an instanton tunneling between the two topological corner states, leading to the oscillation of tunneling currents.

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Electronic structures and interactions in graphene moiré superlattices

Hyoung Joon Choi
Department of Physics, Yonsei University, Seoul 03722, Korea
h.j.choi@yonsei.ac.kr

Twisted graphene layers show large-scale moiré superlattices in their atomic structures and have almost flat bands in their electronic structures. Detailed band structures of the almost flat bands are sensitive to the twist angle, the number of layers, the stacking configuration, doping, and applied electric fields [1-4]. Here, we discuss band dispersions of the almost flat bands as a function of doping, electric fields, the twist angle, and the number of layers. We also discuss strength of the electron-phonon interaction and the superconductivity in different twisted graphene layers [3]. We further discuss spin-valley polarized phases as a function of doping, based on the density functional theory calculations [4]. This work was supported by NRF of Korea (Grant No. 2020R1A2C3013673) and KISTI supercomputing center (Project No. KSC-2021-CRE-0384).

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Tunable Magnetism and Excitonic Effects in 2D Magnetic Semiconductors

Ting Cao

Department of Materials Sciences and Engineering, University of Washington, Seattle, Washington 98195, United States

tingcao@uw.edu

In two-dimensional (2D) van der Waals (vdW) magnets, the interlayer coupling is highly tunable. This talk will show our recent theoretical and computational studies of magnetism and exciton physics in 2D magnets such as CrI_3 and CrSBr. Based on first-principles density functional theory (DFT) and GW Bethe-Salpeter equation (GW-BSE) calculations, we show that 2D magnetic semiconductors exhibit a rich set of excitons of Frenkel or Wannier types, which encode excited-state information dictated by the underlying crystal structure and magnetic order. We then present our recent studies of tunable magnetism by strain and other means, which leads to controllable interlayer couplings and results in distinct optical properties in 2D magnetic semiconductors. We further connect our theoretical discoveries to experimental results and explore their potential applications.

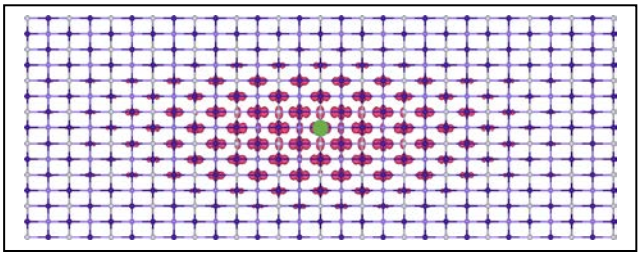

Fig 1. Wannier Exciton in a 2D magnet, CrSBr.

Structure, Properties and Growth of 1D van der Waals Heterostructures – Computational Challenges

Nicholas Ansell,[1] Sophie Baker,[1] Josh Brown,[1] Jemma Lawrence,[1] Ben D. McLean,[1,2] **Alister J. Page,[1]*** Daniel S. Vadseth[1]

[1] *Discipline of Chemistry, University of Newcastle, Australia*

[2] *Center for Multidimensional Carbon Materials (CMCM), Institute for Basic Science (IBS), Republic of Korea*

alister.page@newcastle.edu.au

Over the last few decades, catalytic chemical vapor deposition (CVD) has matured as a synthetic technique for producing many low-dimensional inorganic nanomaterials, such as carbon nanotubes (CNTs), graphene, boron nitrides and transition metal dichalcogenides. The general mechanism of graphene and CNT formation during CVD is now well established [1]. In contrast to carbon nanomaterials, little is known regarding the catalytic pathways underpinning CVD synthesis of other inorganic nanotubes, for instance boron nitride nanotubes [1]. However, the synthesis of 1D van der Waals heterostructures [2] means that understanding the formation mechanisms of these, and other inorganic nanostructures, has never been more important.

However, 1D van der Waals heterostructures present unique challenges to computational approaches - in this lecture I will discuss our recent work aimed at overcoming these barriers, and discuss structure-property relationships in various 1D van der Waals heterostructures. I will also discuss the nucleation mechanism of boron nitride nanotubes (BNNTs) observed during reactive molecular dynamics simulations of boron oxide / ammonia borane CVD [3-5]. This novel mechanism, whereby BNNTs nucleate via a 'network fusion' mechanism, and the factors that control it provide useful insight towards controlling the synthesis of new van der Waals heterostructures.

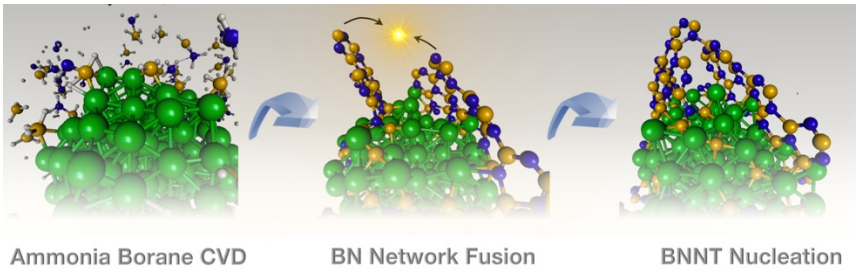

Figure 1. Network fusion nucleation of BNNTs during Ni-catalysed ammonia borane CVD.

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Atomistic simulations of carbon nanotube growth using machine learning force fields – from a clean Fe cluster to a fully grown tube

Daniel Hedman [a], Ben McLean [a], J. Andreas Larsson [b] and Feng Ding [a, c]

[a] *Center for Multidimensional Carbon Materials (CMCM), Institute for Basic Science (IBS), Ulsan 44919, Republic of Korea*

[b] *Applied Physics, Division of Materials Science, Department of Engineering Sciences and Mathematics, Luleå University of Technology, Luleå SE-971 87, Sweden*

[c] *School of Materials Science and Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, Republic of Korea*

Atomistic simulation of the carbon nanotube (CNT) growth process, from a clean Fe cluster to a fully grown tube, is challenging due their slow growth rate/defect healing. This prevents us from using accurate techniques such as density functional theory (DFT) or density functional based tight binding to model this process. At the same time, the accuracy of classical force fields (FF) is not good enough to correctly describe the growth process. To solve this, we train a state-of-the-art deep neural network potential on reference data from DFT calculations to develop a Fe-C machine learning force field (MLFF) which combines the accuracy of DFT with speed of classical FFs. This enables us to study, at the atomic level, the growth dynamics of CNTs with unprecedented accuracy at timescales of hundreds of ns to µs. Our current Fe-C MLFF has an RMSE of 11.0 meV per atom in energy and 0.359 eV/Å in forces and can simulate CNT growth at ~70 ns per day (70 000 000 timesteps) using a single Nvidia V100 GPU.

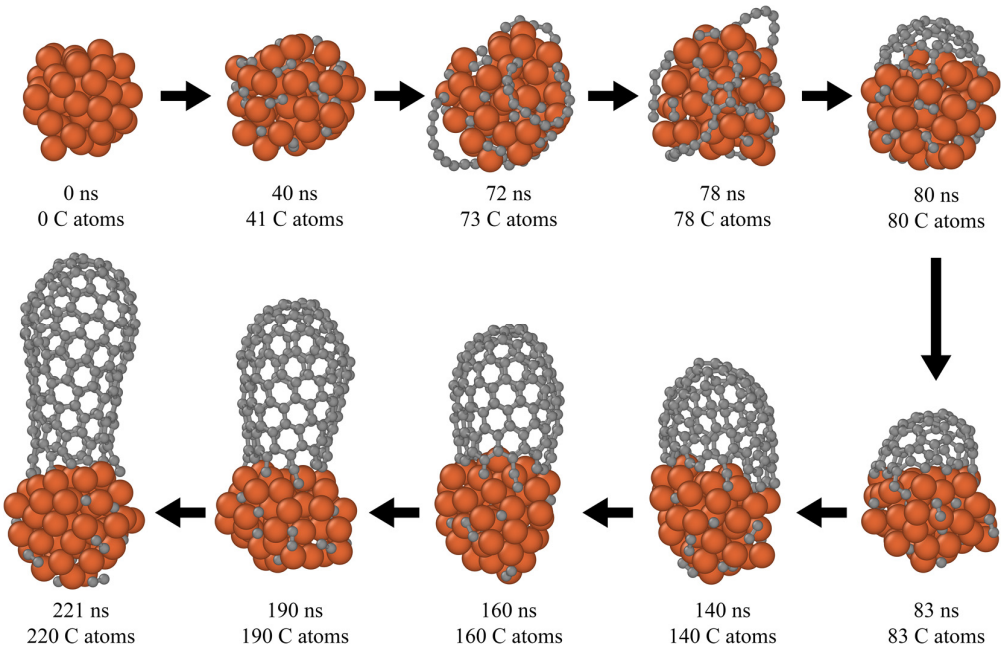

Fig 1. Results from one continuous molecular dynamics simulation using our Fe-C MLFF of CNT growth at 1500 K. Starting from a clean Fe_{55} cluster (0 ns) to the formation of C dimers on the catalyst surface (40 ns). Dimers coalescing to form long C chains (72 ns) and the nucleation of the first C ring (pentagon) from 4 chains (78 ns). The continuous formation of rings creates a CNT cap (80 ns) which lifts off from the catalyst (83 ns) and continues to grow to a fully formed tube (140 to 221 ns).

Topological edge and corner states and fractional corner charges in blue phosphorene

Tenta Tani, Masaru Hitomi, Takuto Kawakami, and Mikito Koshino
Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
tenta.tani@qp.phys.sci.osaka-u.ac.jp

In this research, we theoretically study edge and corner states in monolayer blue phosphorus (blue phosphorene) by using first-principles calculations and tight-binding models.

In monolayer black phosphorus (black phosphorene), the existence of edge and corner states has already been shown[1]. However, in its allotrope, blue phosphorene, the topological origin of the edge and corner states has not been clarified.

We reveal that the emergence of the edge states in zigzag and armchair nanoribbons are due to the center position of the Wannier orbital (Wannier center)[2]. When a Wannier orbital is broken at the boundary of the system, the corresponding edge state appears. The nature of the edge states can be explained by considering an effective Hamiltonian where we focus on only the uncoupled orbitals at the boundary of the system.

In addition, we examine the corner states in zigzag- and armchair-type nanoflakes. We find that there emerge multiple corner states in both nanoflakes. They can also be explained by a simple effective Hamiltonian in the same way as the case of the nanoribbons. Especially, in the armchair nanoflake, a corner state appears right at the Fermi energy, by the effect of a surface reconstruction. Remarkably, this corner state causes $e/2$ fractional corner charges[3].

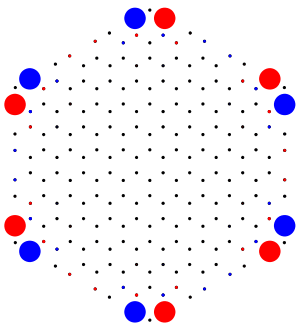

Fig.1 The corner-state wavefunction right at the Fermi energy in the armchair nanoflake. The black dots represent atoms, the radii of disks stand for the amplitudes $|\psi|$ and red/blue colors stand for the signs of the real part $Re\psi$.

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The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

Parallel Symposia Program & Abstract

Bio

Parallel Symposia **BIO @ Chemistry Building # 330110**

Thursday, JUNE 23rd, 2022

		Chair: Dan Heller (sloan kettering)
14:30-15:00	P-Bi-I1	**Yutaka Majima** (Tokyo Institute of Technology, Japan) *Nanogap Gas Sensors and Electroless Au-Plated Nanopore DNA Sequencer*
15:00-15:30	P-Bi-I2	**Laurent Cognet** (CNRS & University of Bordeaux, France) *Single carbon nanotube localization microscopy reveals brain extracellular space landscapes around synapses and in neurodegenerative conditions*
15:30-15:40	Short break	
		Chair: Woo-Jae Kim (Ehwa Womans University)
15:40-16:10	P-Bi-I3	**Gili Bisker** (Tel Aviv University, Israel) *In vivo imaging of fluorescent single-walled carbon nanotubes within C. elegans nematodes*
16:10-16:40	P-Bi-I4	**Jong-Ho Kim** (Hanyang University, Korea) *2D-TMD Antibody Mimics for Diagnosis and Therapy of Bacterial Infections*
16:40-17:00	P-Bi-C1	**Sanghwa Jeong** (Pusan National University, Korea) *Optical Nanoprobes for Dynamic Neurochemical Imaging*

Friday, JUNE 24th, 2022

		Chair: Gyu Jin Cho (Sungkyunkwan University)
13:15-13:45	P-Bi-I5	**Markita Landry** (University of California Berkeley, USA) *Imaging Neuromodulation in the Brain with Near-Infrared Fluorescent Nanosensors*
13:45-14:05	P-Bi-C2	**Nicole Iverson** (University of Nebraska Lincoln, USA) *Removable, Real Time Carbon Nanotube Sensors for Long-term in Vivo Analysis*
14:05-14:25	P-Bi-C3	**Chaejeong Heo** (Sungkyunkwan University, Korea) *New strategy of molecular structure-specific label-free THz monitoring for Alzheimer's disease diagnosis*
14:25-14:35	Short break	
14:35-14:55	P-Bi-C4	**Mijin Kim** (Memorial Sloan Kettering Cancer Center, USA) *Machine-learning-enabled nanosensor array to detect a disease fingerprint*
14:55-15:25	P-Bi-I6	**Tae-il Kim** (Sungkyunkwan University, Korea) *Unconventional Band Pass Filters for Bioelectronics*

Nanogap Gas Sensors and Electroless Au-Plated Nanopore DNA Sequencer

Yutaka Majima

Laboratory for Materials and Structures, Institute of Innovative Research,
Tokyo Institute of Technology
majima@msl.titech.ac.jp

Gas sensors have been widely used for many industrial processes, biomedicine, and environmental monitoring applications. Many researchers have focused on developing and improving gas-sensing technologies. At the frontier of this evolving field lie modern nanogap gas sensors—devices usually comprised of a sensing material and two conducting electrodes that are separated by a minuscule gap in the order of nanometers (nm). When molecules of specific gases get inside this gap, they electronically interact with the sensing layer and the electrodes, altering measurable electric properties such as the resistance between the electrodes. In turn, this allows one to indirectly measure the concentration of a given gas. Although nanogap gas sensors bear many more attractive properties than the closely related microgap gas sensors, they have proven much more difficult to mass produce reliably for gap separations in the order of tens of nanometers. In this study, we present a strategy to produce nanogap oxygen gas sensors using platinum/titanium (Pt/Ti) electrodes and a cerium oxide (CeO_2) sensing layer. This nanogap gas sensors could be promising candidates for the development of a general gas-sensing platform with a low operating temperature with high response speed. The nanogap gas sensors should find their way into more fields of application, including wearable biomedical devices, industrial condition monitoring, and environmental sensing.

DNA sequencing is technique to determine the exact sequence of bases (adenine, cytosine, guanine, and thymine) in a DNA molecule. The DNA base sequence carries the information of a cell for assembling protein and RNA molecules. DNA sequence information is important for investigating the functions of genes. Various DNA sequencing techniques have been developed such as Sanger sequencing, capillary electrophoresis and fragment analysis, and next-generation sequencing. Nanopore DNA sequencing is one of the techniques for long-read sequencing, which enables direct, real-time analysis for long DNA. Changes in electrical current are monitored owing to nucleic acids passed through nanopore. Protein nanopore and SiN nanopore have been used. In this study, we also present metallic nanopore DNA sequencing. We prepare Pt initial nanopore with the pore diameter of 30 nm. Pore diameter is narrowed down to 2 nm by heteroepitaxial electroless Au-plating (ELGP). We will demonstrate ELGP nanopore DNA sequencing.

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Single carbon nanotube localization microscopy reveals brain extracellular space landscapes around synapses and in neurodegenerative conditions

Laurent Cognet
CNRS & University of Bordeaux
LP2N - Institut d'Optique, rue François Mitterrand, Talence, France
laurent.cognet@u-bordeaux.fr

Single-molecule localization microscopy (SMLM) has set a new paradigm in the field of optical imaging, especially in bioscience to study structural and dynamic arrangements of the matter at the nanoscale. As a member of the "super-resolution microscopy" family SMLM indeed provides optical images with resolutions well beyond the diffraction limit. Yet, it remains challenging to study more complex systems than isolated nanostructures or isolated living cells in biology with such approaches. For instance, SMLM in thick and intact brain tissues is penalized by the limited brightness of fluorescent emitters, the optical aberrations induced by the samples and/or the poor penetration of the light into biological tissue at visible wavelengths.

To circumvent these limitations and investigate live brain tissues, we developed a framework based on SMLM and single-wall carbon nanotube near-infrared imaging [1]. Nanotube detection and tracking at the single nanotube level allow the extracellular space of intact live brain tissues to be revealed at the nanoscale.

We will show that this approach can be applied to reveal the precise organization of pathological ECS in adult mice under degenerative conditions (α-synuclein-induced neurodegeneration) [2]. It is found that these animals display a degraded hyaluronan matrix in areas close to reactive microglia which induces increased ECS diffusivity and dimensions, highlighting hyaluronan as diffusional barrier and local tissue organizer.

Another application concerns the investigation of the brain ECS around synapses. We reveal specific ECS properties in terms of morphology at the nanoscale and inner diffusivity which are modulated upon synaptic activity [3].

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See also: www.cognet-research.com

In vivo imaging of fluorescent single-walled carbon nanotubes within C. elegans nematodes

Gili Bisker
Tel Aviv University
Department of Biomedical Engineering, Faculty of Engineering, Tel Aviv, 6997801, Israel
bisker@tauex.tau.ac.il

Caenorhabditis elegans (*C. elegans*) nematodes serve as a model organism for eukaryotes, especially due to their genetic similarity. However, their autofluorescence in the entire visible wavelength range poses a challenge for imaging and tracking fluorescent proteins or dyes using standard fluorescence microscopy. Herein, near-infrared (NIR) fluorescent single-walled carbon nanotubes (SWCNTs) are utilized for *in vivo* imaging within the gastrointestinal track of *C. elegans* [1-3]. The SWCNTs are biocompatible, and do not affect the worms' viability nor their reproduction ability. The worms do not show any autofluorescence in the NIR range, thus enabling the spectral separation between the SWCNT NIR fluorescence and the strong autofluorescence of the worm gut granules. These biocompatible, non-photobleaching, NIR fluorescent nanoparticles can advance *in vivo* imaging and tracking within *C. elegans* and other small model organisms by overcoming the signal-to-noise challenge stemming from the wide-range visible autofluorescence [4-7].

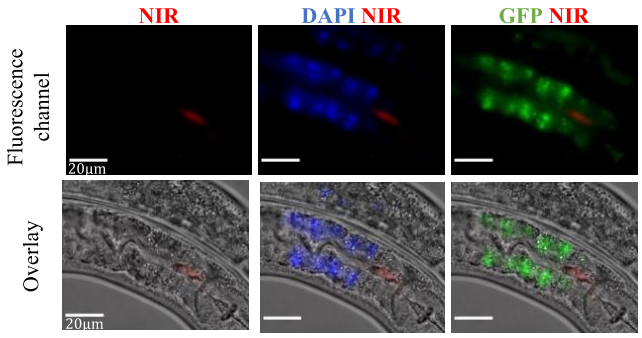

Fig 1. Fluorescence images of the SWCNTs in the NIR (red), SWCNTs with auto-fluorescence in the DAPI channel (red and blue), and SWCNTs with autofluorescence in the GFP channel (red and green) on the top row. The bottom row is the overlaid images of the brightfield and the fluorescence. The scale bar is 20 μm.

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2D-TMD Antibody Mimics for Diagnosis and Therapy of Bacterial Infections

Jong-Ho Kim*

Department of Materials Science and Chemical Engineering, Hanyang University, Ansan, 15588, Republic of Korea.

**kjh75@hanyang.ac.kr*

Antibodies are widely employed as recognition elements in diagnosis and therapy of various diseases [1], however, they have some limitations such as poor stability, long discovery time, and high cost. Herein, a facile approach to create nanohybrid antibody mimics with multivalent peptide recognition phases and luminescent rigid transition metal dichalcogenide (TMD) nanosheets for the selective recognition, detection, and eradication of pathogenic bacteria is presented. Tripeptides with a nitriloacetate-Cu group were spontaneously assembled on TMD nanosheets *via* coordinate bonding, providing a variety of TMD-tripeptide assembly (TPA) antibody mimics [2]. TMD-TPA antibody mimics selectively recognized various pathogenic bacteria, including *E. coli* O157:H7, *S. aureus*, and *S. typhimurium*, with high binding affinities. The bacterial binding sites for TMD-TPA were identified by experiments and molecular dynamics simulations, revealing that the dynamic and multivalent interactions of TMD-TPA antibody mimics played an important role for their selective recognition and high affinity. The TMD-TPA antibody mimics allowed the rapid, selective, and sensitive detection of pathogenic bacteria from human serum and urine. In addition, the TMD-TPA antibody mimics selectively killed the pathogenic bacteria infecting the wounds of mice under near-infrared irradiation, leading to effective healing. This work demonstrates the potential of TMD-TPA antibody mimics as an alternative to protein antibodies for diagnosis and therapy.

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Optical Nanoprobes for Dynamic Neurochemical Imaging

Sanghwa Jeong
School of Biomedical Convergence Engineering, Pusan National University, Korea
Sanghwa.jeong@pusan.ac.kr

Release and reuptake of neuromodulator serotonin is central to mood regulation and neuropsychiatric disorders, whereby imaging serotonin is of fundamental importance to study the serotonin signaling system. Recently, I present a reversible near-infrared optical probe for serotonin that reports physiologically-relevant serotonin concentrations on relevant spatiotemporal scales, and is compatible with pharmacological tests. Synthetic molecular recognition for serotonin was conferred by evolving molecular recognition between single stranded DNA (ssDNA) and single-walled carbon nanotube (SWNT). To do so, we developed a high-throughput screening platform for evolution of serotonin molecular selectivity, in which systematic evolution of ligands by exponential enrichment is implemented on carbon nanotube surfaces, a process we've termed SELEC. Our results suggest evolution of nanosensors could be generically implemented to rapidly develop other neuromodulator probes, and that these probes can image neuromodulator dynamics at spatiotemporal scales compatible with endogenous neuromodulation. Furthermore, with the help of machine-learning classification and regression model from SELEC DNA library, we extended the high-throughput screening capability to fabricate the highly-sensitive serotonin nanosensor.

Imaging Neuromodulation in the Brain with Near-Infrared Fluorescent Nanosensors

Markita P. Landry
University of California Berkeley
201 Gilman Hall, UC Berkeley, Berkeley, CA 94702
landry@berkeley.edu

Neurons communicate through chemical neurotransmitter signals that either terminate at the postsynaptic process ("wired transmission") or diffuse beyond the synaptic cleft to modulate the activity of larger neuronal networks ("volume transmission"). Molecules such as dopamine, serotonin, and neuropeptides such as oxytocin belong to the latter class of neurotransmitters, and have been the pharmacological targets of antidepressants and antipsychotics for decades. Owing to the central role of neuromodulators such as dopamine over a range of behaviors and psychiatric disorders, real-time imaging of the signal's spatial propagation would constitute a valuable advance in neurochemical imaging. To this end, we present a library of nanoscale near-infrared fluorescent nanosensors for dopamine, serotonin, and oxytocin, where the nanosensors are developed from polymers pinned to the surface of single wall carbon nanotubes (SWNT) in which the surface-adsorbed polymer is the recognition moiety and the carbon nanotube the fluorescence transduction element. Excitonic transitions in functionalized SWNT yield up to $\Delta F/F$ = 4500% near-infrared fluorescence emission in the presence of dopamine (Beyene *et al. Nano Letters* 2018), $\Delta F/F$ = 200% for serotonin (Jeong *et al. Science Advances* 2019), and $\Delta F/F$ = 120% for oxytocin (unpublished). We next demonstrate imaging of evoked dopamine release in acute striatal slices (Yang *et al. Nature Protocols* 2021), and show altered dopamine reuptake kinetics when brain tissue is exposed to dopamine receptor agonist and antagonist drugs (Beyene *et al. Science Advances* 2019). We characterize our findings in the context of their utility for high spatial and temporal neuromodulator imaging in the brain, describe nanosensor exciton behavior from a molecular dynamics (MD) perspective, and validate nanosensor for use to elucidate dopaminergic signaling variability in Huntington's Disease at a synaptic scale.

REMOVABLE, REAL TIME CARBON NANOTUBE SENSORS FOR LONG-TERM IN VIVO ANALYSIS

Nicole M Iverson
University of Nebraska Lincoln
Department of Biological Systems Engineering, 260 Morrison Hall, 4240 Fair Street, Lincoln, NE 68583, United States of America
iverson@unl.edu

Carbon nanotube sensors have great potential for in vivo detection of a variety of analytes. Unfortunately, we do not know the long-term impact of carbon nanotubes within the body. To avoid this complication, my lab has created implantable carbon nanotube sensor platforms that remain intact and can be removed from the body without leaving any carbon nanotubes behind. The incorporation of carbon nanotube sensors into a platform frequently alters the sensor response time, so real-time detection of animal/human health is not possible. We have overcome this problem by keeping the sensors in a liquid state, utilizing a 3D Bioplotter to create precise, intricate hydrogels that can deliver multiple carbon nanotube sensors in liquid form to the body while retaining the nanotubes for removal post-analysis. This new technology will allow for carbon nanotube sensor use in vivo without concerns over long-term toxicity issues.

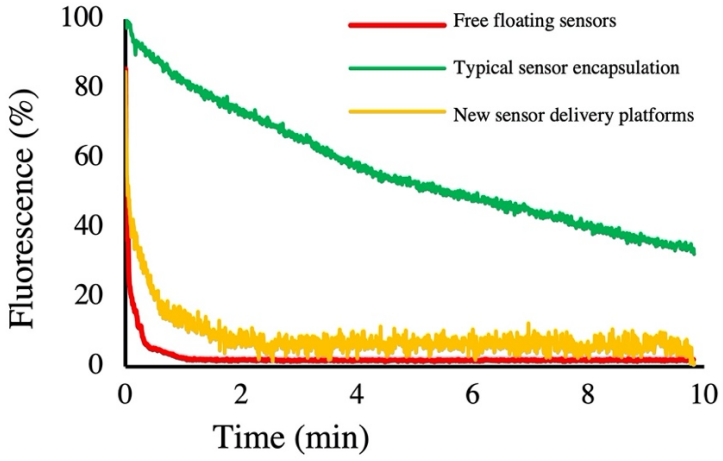

Fig 1. Typical carbon nanotube sensor encapsulation schemes (green) result in delayed response time compared to free floating sensors (red). Our new carbon nanotube encapsulation platform (yellow) results in real time sensor response.

New strategy of molecular structure-specific label-free THz monitoring for Alzheimer's disease diagnosis

Chaejeong Heo [a, b]

[a]*Center for Integrated Nanostructure Physics (CINAP), Institute for Basic Science (IBS), Suwon 16419, Republic of Korea.*
[b]*Institute for Quantum Biophysics (IQB), Department of Biophysics, Sungkyunkwan University, Suwon 16419, Republic of Korea*
cjheo@skku.edu

Since amyloid β (Aβ) proteins can be accumulated at early Alzheimer's disease (AD) stages in the brain tissue, a various Aβ aggregates has been linked with severity of AD and the primary biomarker for early-stage diagnosis as well as drug treatment. Our group recently developed the water-based near-field terahertz (THz) spectroscopy technique to measure Aβ in solution [1]. By noting monotonic conductance change with frequency in monomers following Drude tail and nonlinear conductance behaviors in oligomers and fibrils adopting the localization parameter in Smith model, we derived a structure-specific discrete metric that we termed dementia quotient (DQ), which is a structurally defined biophysical index of Aβ aggregation state with modified Drude-Smith model [1]. Furthermore, we investigate Aβ protein dynamics to identify various morphological phase transitions from monomers to fibrils under physiological conditions by monitoring the structure-specific DQ values. The time evolution of these morphological phase transformations is well described in terms of universal rate-limiting equation scaled by kinetic parameters; transition time and growth rate [2]. Our method could ultimately facilitate the early AD diagnosis in a nanomolar limit with drop-sized peripheral solution samples.

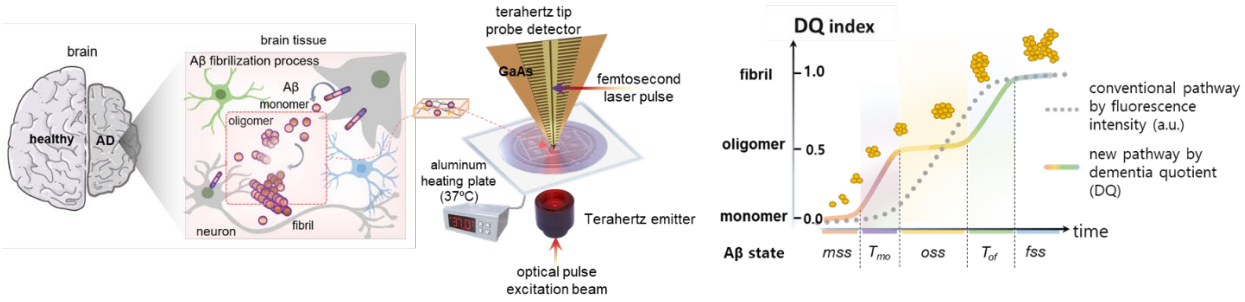

Fig.1 Schematics for the rate-limiting, stepwise Aβ protein states of by Dementia Quotient (DQ) for diagnosis of Alzheimer's disease (AD) using by near-field THz spectroscopy.

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Machine-learning-enabled nanosensor array to detect a disease fingerprint

Mijin Kim
Molecular Pharmacology Program, Memorial Sloan Kettering Cancer Center, New York, NY 10065, United States
kimm7@mskcc.org

Organic color centers (OCCs) are synthetic quantum defects incorporated into semiconducting single-walled carbon nanotubes by the covalent attachment of functional groups to the nanotube sidewalls [1]. OCCs feature extraordinary traits that make them ideal materials for biomedical applications: First, the OCC-induced photoluminescence confers new sensitivities determined by the chemical nature of the defect, making OCCs the molecular focal points for chemical detection. Second, the OCC photoluminescence is extremely sensitive to the local microenvironment and can be systematically controlled by tailoring the functional defects. Such structural diversity and chemical sensitivity of OCCs can be translated into a rich family of biochemical probes that sensitively and selectively respond to diverse classes of analytes. Herein, we present the acquisition of a 'disease fingerprint' using machine learning operations on near-infrared photoluminescence spectral data from an array of OCC-modified carbon nanotubes in patient sera. The diverse spectral responses of the sensor array, processed by data analytics, collectively determine the disease state [2] and the levels of disease biomarkers [3].

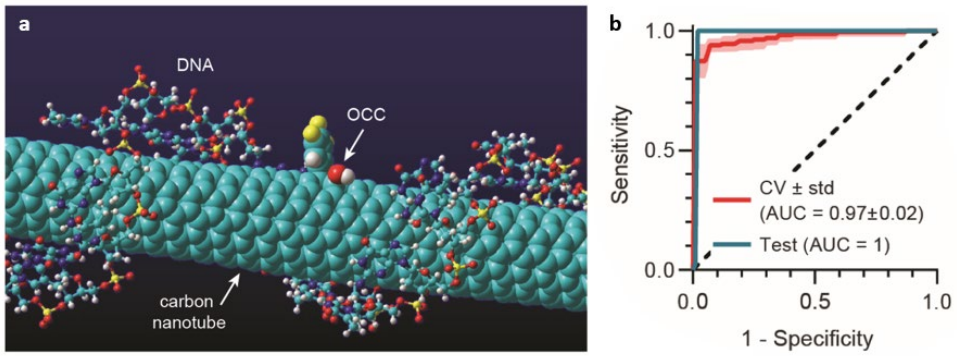

Fig.1 | OCC-DNA nanosensor array for ovarian cancer detection. a, Molecular model of an OCC-based nanosensor element. Shown is a ss$(GT)_{15}$ DNA-wrapped (6,5)-SWCNT with 3,4,5-trifluoroaryl OCC. **b,** Best ROC curves for binary classification of ovarian cancer, showing both cross-validated training set (CV) and test/validation set (Test).

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Unconventional Band Pass Filters for Bioelectronics

Tae-il Kim
School of Chemical Engineering, Sungkyunkwan University (SKKU)
Suwon Korea
taeilkim@skku.edu

Biophysiology detection from current advanced electronics is limited by external signal artifacts (e.g. walking and respiration).[1] Here, we present the viscoelastic gelatin/chitosan hydrogel damper inspired by the viscoelastic cuticular pad in a spider to remove dynamic mechanical noise artifacts selectively under 30 Hz. [2] The hydrogel exhibits frequency-dependent phase transition that results in a rubbery state that damps low-frequency noise and a glassy state that transmits the desired high-frequency signals. Instead of the conventional signal processing, the hydrogel damper served as unconventional pass filter that is able to be integrated with advanced bioelectronics for biophysiology detection even in noisy conditions. Also several methods for band pass filtering for human physiological signals will be discussed. [3, 4] It can dissolve chronic noise problems in the bioelectronics, and shows huge potential for uninterrupted monitoring of devices (i.e., gadgets, medical devices, or prostheses) for patients.

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The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

Parallel Symposia Program & Abstract

Synthesis

Parallel Symposia **SYNTHESIS @ Chemistry Building # 330118**

Monday, JUNE 20th, 2022

		Chair: Seung Min Kim (KIST)
14:30-15:00	P-Sy-I1	**Shigeo Maruyama** (The University of Tokyo, Japan) *Chemical Vapor Deposition synthesis of 1D vdW heterostructures based on SWCNTs*
15:00-15:30	P-Sy-I2	**Sofie Cambré** (University of Antwerp, Belgium) *Shedding light on the mechanisms of aqueous two-phase separation of single-wall carbon nanotubes*
15:30-15:40	Short break	
		Chair: IL Jeon (Sungkyunkwan University)
15:40-16:10	P-Sy-I3	**Jaegeun Lee (**Pusan National University, Korea) *Decoupling Catalyst Dewetting, Gas Decomposition, and Surface Reactions in Carbon Nanotube Forest Growth*
16:10-16:40	P-Sy-I4	**Yuan Chen** (The University of Sydney, Australia) *Synthesis, purification, and applications of carbon onions from catalytic methane decomposition on iron ore catalysts*
16:40-17:00	P-Sy-C1	**Miguel Vazquez Pufleau** (IMDEA, Spain) *Kinetic insight for CNT synthesis via floating catalyst provided by decoupling Fe nanoparticle formation, S promoter addition and C decomposition*

Tuesday, JUNE 21st, 2022

		Chair: Paola Ayala (University of Vienna)
14:30-15:00	P-Sy-I5	**Jing Kong** (Massachusetts Institute of Technology, USA) Engineering, Korea) *Synthesis and Integration of Carbon Nanotubes for Electronics Applications*
15:00-15:30	P-Sy-I6	**Wencai Ren** (Chinese Academy of Sciences, China) *Discovery of layered 2D MoSi2N4 family*
15:30-15:40	Short break	
		Chair: Myung Jong Kim (Gachon University)
15:40-16:00	P-Sy-C2	**Byeong Wook Cho** (Sungkyunkwan University, Korea) *Facile substitutional metal doping in two-dimensional transition metal dichalcogenides by liquid-phase precursor mixing*
16:00-16:20	P-Sy-C3	**Soo Ho Choi** (Sungkyunkwan University, Korea) *Single-crystal growth of transition metal dichalcogenide films on atomic sawtooth Au surface*
16:20-16:50	P-Sy-I7	**Qingwen Li** (Suzhou Institute of Nano-Tech and Nano-Bionics, China) *Multifunctional CNT films: Scalable synthesis and applications*

Chemical Vapor Deposition synthesis of 1D vdW heterostructures based on SWCNTs

Shigeo Maruyama
Department of Mechanical Engineering, The University of Tokyo
The University of Tokyo, Tokyo 113-8656, Japan
maruyama@photon.t.u-tokyo.ac.jp

A typical one-dimensional (1D) van der Waals (vdW) heterostructure consists of coaxial single-walled carbon nanotubes (SWCNT), boron nitride nanotube (BNNT), and molybdenum disulfide nanotube (MoS_2NT) [1]. The coaxially nested structure based on SWCNTs, which has various electronic properties (metallic or semiconducting), can expand the board application possibilities of 1D vdW heterostructures [2-6]. Semiconductor SWCNT wrapped with BNNT can be regarded as the ideal building blocks of field-effect transistors (FET) [2]. We have demonstrated the radial semiconductor–insulator–semiconductor (S-I-S) tunneling heterojunction diode by using a micrometer long 1D vdW heterostructure SWCNT@BNNT@MoS_2NT [7]. By comparing optical properties of films of BNNT@MoS_2NT and SWCNT@BNNT@MoS_2NT, we found strong photoluminescence (PL) from monolayer MoS_2NT and quenching of PL by coupling to SWCNT through thin BNNT [8]. The large population of free charges and inter-tube excitons are demonstrated by ultrafast optical spectroscopy [9]. The inter-tube excitions are similar to inter-layer excitions for 2D heterostructures.

Precise control of each layer's chemical vapor deposition (CVD) process is essential since the mechanical exfoliation & stacking technique for 2D counterpart is not possible for 1D vdW heterostructures. The challenges are both CVD growth of BNNT and nanotubes of transition metal dichalcogenides (TMDC). We have been optimizing BNNT growth on suspended SWCNTs, chirality-sorted SWCNTs, film of SWCNTs, and vertically aligned SWCNTs. The surprisingly sharp edge of BNNT grown on SWCNT is the signature of preference of nitrogen terminated zig-zag edge of h-BN common to 2D counterpart [10]. The next challenge is the CVD growth of various TMDC nanotubes on BNNTs. In addition to MoS_2 nanotubes [1], we will discuss the growth control of WS_2 nanotubes and NbS_2 nanotubes. A general strategy we can tune the CVD condition from 2D flake to 1D tube is proposed [11].

Part of this work was supported by JSPS KAKENHI Grant Number JP20H00220 and by JST, CREST Grant Number JPMJCR20B5, Japan.

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Shedding light on the mechanisms of aqueous two-phase separation of single-wall carbon nanotubes

M. V. Avramenko, J. Defillet, M. Martinati, M. A. Lopez Carrillo, D. Van der Elst, W. Wenseleers and S. Cambré

Nanostructured and Organic Optical and Electronic Materials, Physics Department, University of Antwerp, Universiteitsplein 1, 2610 Antwerp, Belgium

sofie.cambre@uantwerpen.be

Separation of single-wall carbon nanotubes (SWCNTs) according to their diameter and chiral structure is imperative to exploit their unique structure-dependent optical and electronic properties in future technologies [1]. Aqueous two-phase extraction (ATPE) has been demonstrated as a fast, highly scalable, and very effective separation technique, allowing for sorting SWCNTs by diameter, chiral structure, electronic properties and handedness [2, 3]. The exact mechanism behind the chirality-dependent migration of SWCNTs between the two phases is however not completely understood, and depends on many parameters making it difficult to optimize the multivariable parameter space by trial-and-error and to attain more control over the separation processes.

In this work, we present a series of ATPE separations, in which surfactant combinations and concentrations are systematically varied. Absorption spectroscopy, multi-wavelength resonant Raman scattering and wavelength-dependent photoluminescence-excitation spectroscopy, combined with detailed two-dimensional spectral fitting, are applied to characterize our samples and to investigate the underlying separation mechanisms. We show that the diameter-dependent stacking of a discrete number of sodium deoxycholate molecules fitting around the circumference of the SWCNTs determines the separation order in the form of a periodically modulated pattern as a function of SWCNT diameter. Similar patterns are obtained for the systematic ATPE experiments involving other bile salt surfactants such as sodium cholate and sodium chenodeoxycholate. Addition of cosurfactants can be used to compete with the bile salt surfactant to enhance the separation yields, but do not seem to affect the sorting order. The results are afterwards directly applied to predict the parameters required to separate specific chiral structures in just two ATPE steps.

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Decoupling Catalyst Dewetting, Gas Decomposition, and Surface Reactions in Carbon Nanotube Forest Growth

Jaegeun Lee

School of Chemical Engineering, Pusan National University, Busan, Republic of Korea, 46241

jglee@pusan.ac.kr

In chemical vapor deposition (CVD) of vertically aligned carbon nanotubes (CNTs), temperatures for the following three processes are typically coupled: (1) catalyst nanoparticle formation by film dewetting, (2) thermal decomposition of gas precursors, and (3) nucleation/growth of CNTs. Here, we present an approach for complete decoupling of these processes using a custom-designed multizone rapid thermal CVD reactor, and introduce two major findings obtained from this approach.

First, we show that in decoupled growth, there is an inverse relationship between density of CNTs and nucleation temperature, while there is no dependence of density on catalyst formation temperature [1]. Importantly, the nucleation/growth temperature that produces the most aligned and densest CNTs is lower than the temperature that produces the tallest CNTs. Second, we show that the CNT yield significantly increased with increasing the catalyst formation temperature [2]. To reveal the mechanism, we combined real-time kinetics measurements with comprehensive characterization of the catalyst and support films after annealing in a reducing environment. Our results reveal that the observed threefold boost in CNT growth at higher catalyst formation temperatures results from increased catalytic lifetime rather than increased reaction rate.

The decoupling approach enables the independent investigation of catalyst preparation, gas phase decomposition, and CNT nucleation processes and allows us to explore a much wider range of experimental parameter space.

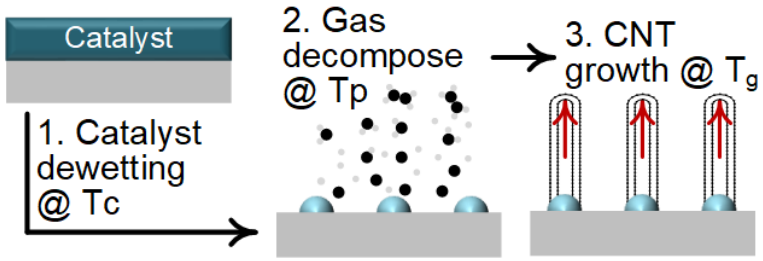

Fig.1 Decoupling of the three processes in the catalytic growth of CNTs.

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Synthesis, purification, and applications of carbon onions from catalytic methane decomposition on iron ore catalysts

Yuan Chen[a]

The University of Sydney, School of Chemical and Biomolecular Engineering, Darlington, New South Wales 2006, Australia

yuan.chen@sydney.edu.au

Catalytic decomposition of methane (CDM) into hydrogen and solid carbon materials ($CH_4 \rightarrow 2H_2 + C$) is a promising approach to achieve environmentally friendly H_2 production. Although CDM can take place on various catalysts, the deposition of solid carbon materials on catalytic metal surfaces quickly deactivates catalysts, making the process uneconomical. Further, large amounts of carbon materials (*i.e.*, H_2 to carbon mass ratio of 1 to 3) are generated as solid wastes. Herein, we show that carbon nano onions encapsulated with magnetic Fe cores (C@Fe) can be produced in CDM on low-cost iron ore catalysts. C@Fe can serve as efficient and recyclable Fenton catalysts for pollutant degradation. C@Fe can be recovered from an aqueous solution and reused due to the encapsulated magnetic Fe particles. Over three reused cycles, C@Fe/H_2O_2 only yields 1/8 of Fe sludges compared to the standard Fenton's reagent $FeSO_4/H_2O_2$, significantly reducing Fe sludge treatment costs. Furthermore, C@Fe can be purified by either standard high-temperature thermal treatment or an alternative electrochemical method to reach the carbon purity of 99.82 and 99.59 wt%, respectively. The purified carbon nano onions show a high electrical conductivity up to 98 S cm^{-1} when incorporated in MnO_2 cathodes and a good electrolyte (1 M ZnSO4) absorption capability up to 4.20 mg mg^{-1}, which are two essential properties for carbon conductive additives. Zinc-carbon batteries assembled using these carbon materials show advantages in electrode conductivity, specific capacity, rate performance, internal resistance, and long-term stability compared with commercial carbon conductive additives. Overall, we demonstrate that carbon materials produced in CDM have excellent potential in water and wastewater treatment and energy applications, making H_2 production via CDM economically more viable.

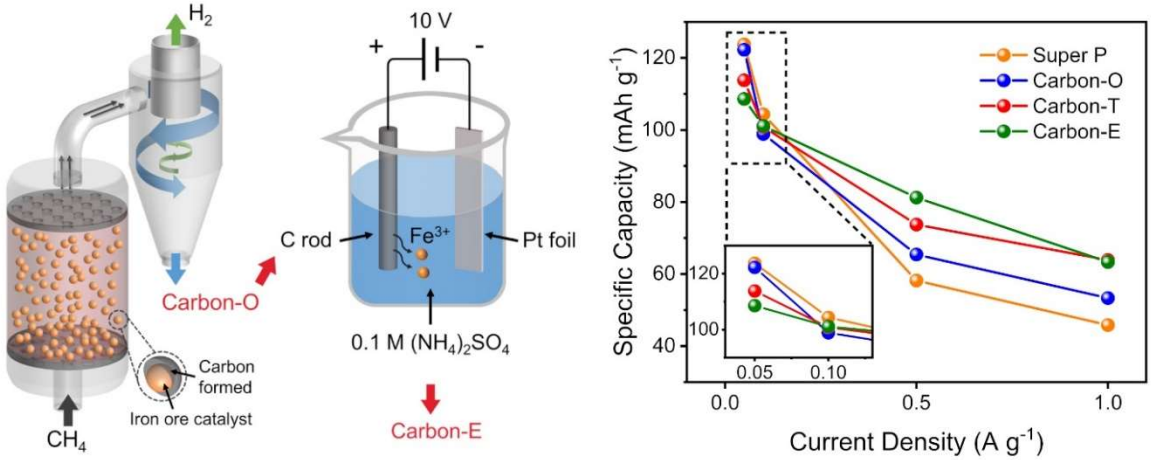

Fig.1 Schematics for carbon onions synthesis, purification, and applications in zinc-carbon batteries.

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Kinetic insight for CNT synthesis via floating catalyst provided by decoupling Fe nanoparticle formation, S promoter addition and C decomposition

Miguel Vazquez-Pufleau[a], Luis Arevalo[a], Anastasiia Mikhalchan[a], Juan Jose Vilatela[a*]
Insituto madrileño de Estudios Avanzados (IMDEA) Materials, Madrid, Spain
Corresponding Address
**juanjose.vilatela@imdea.org*

The effect of sulfur on the iron catalyst for the synthesis of carbon nanotubes via floating catalyst has been reported to be critical for two reasons. Firstly, it prevents the naturally occurring agglomeration and sintering of the iron catalyst limiting its inactivation via this route. Secondly, S is the promoter of CNT formation, so it is essential to control its concentration in the catalyst [1]. Several studies report the importance of the ratio of Fe, S and C [2], However, few have achieved to decouple their kinetic evolution as most studies report the addition of the precursors for these 3 materials together at the inlet of the reactor. Therefore, those systems are typically subject to competitive diffusion limitations, which inactivate the catalyst and limit yield. Some studies have suggested that injecting the precursors separately at different heights of the reactor can have a positive impact on CNT yield and quality [3]. In this work, we have completely decoupled the availability of these 3 precursors for CNT synthesis from one another. For the generation of iron, we have developed a spark discharge generator. The Fe nanoparticles are then mixed with S vapor produced via a thermal sublimator. Finally, a C source is injected into the reactor using a syringe pump. By separating the processes, we are able to study the kinetics of the synthesis of CNTs from a mechanistic point of view and use different limiting conditions than the ones typically found on the literature. This provides a novel perspective and insight on the kinetics and mechanistic route of CNT synthesis.

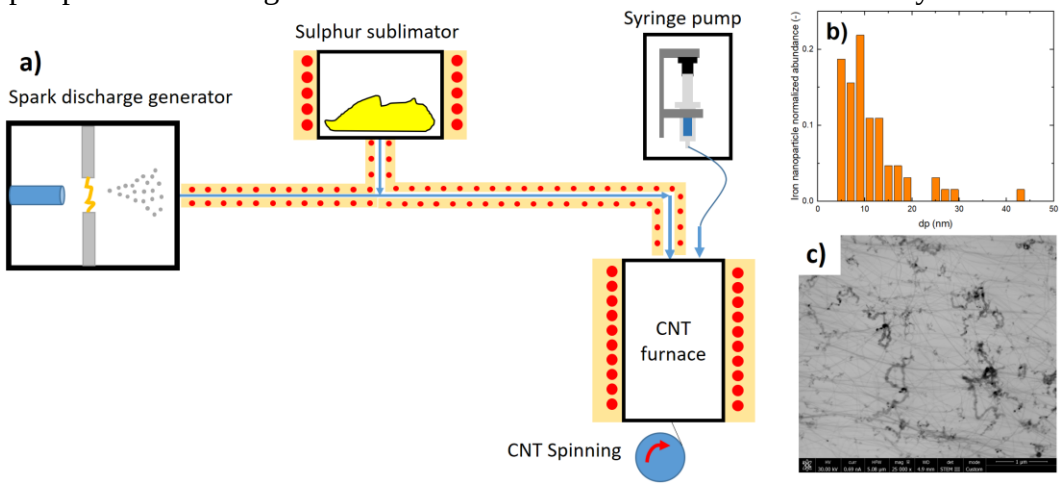

Fig 1. a) Setup schematics of CNT synthesis via Floating catalyst. Example of how the size distribution of b) catalyst generated have a direct impact on the c) CNTs obtained

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Synthesis and Integration of Carbon Nanotubes for Electronics Applications

Jing Kong
Massachusetts Institute of Technology
77 Mass Ave., Cambridge, MA 02139
jingkong@mit.edu

The remarkable structures and properties of carbon nanotubes (CNT) have attracted tremendous interests in research for the past several decades. For electronics applications, efficient integration and controlled growth of pure semiconducting/metallic type of CNTs are highly desirable. In this talk I will present out recent development on a soft-lock drawing method to obtain super-aligned CNT bundles and explorations to use them for nanometer electrical contacts applications. I will also talk about our studies continuing from the electric field twisted chirality of metallic CNTs into semiconducting CNTs for CNT devices applications.

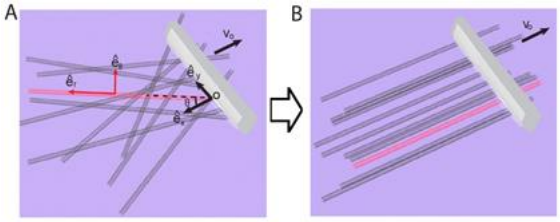

Fig 1. Schematics of angular and linear momentum models for CNT alignment.

Discovery of layered 2D $MoSi_2N_4$ family

Wencai Ren*
Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang, 110016
wcren@imr.ac.cn

Identifying 2D layered materials in the monolayer limit has led to discoveries of numerous new phenomena and unusual properties. We have developed a chemical vapor deposition (CVD) method to grow high-quality nonlayered 2D transition metal carbides/nitrides with diverse structures. However, these nonlayered materials tend to grow as islands rather than layers because of surface energy constraints. Recently, we introduced elemental silicon during CVD growth of non-layered molybdenum nitride to passivate its surface dangling bonds, which enabled the growth of centimeter-scale monolayer films of a new van der Waals layered material, $MoSi_2N_4$. This monolayer was built up by septuple atomic layers of N-Si-N-Mo-N-Si-N, which can be viewed as a MoN_2 layer sandwiched between two Si-N bilayers. This material exhibited semiconducting behavior (bandgap, ~1.94 eV), high strength (~66 GPa), and excellent ambient stability. Density functional theory calculations predict a large family of such monolayer structured 2D layered materials, including semiconductors, metals, magnetic half-metals, superconductors, and topological insulators, which are expected to have promising applications in electronics, spintronics, valleytronics, optoelectronics, energy conversion and storage, and thermal management.

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Facile substitutional metal doping in two-dimensional transition metal dichalcogenides by liquid-phase precursor mixing

Byeong Wook Cho [a, b] and Young Hee Lee [a,b]

[a] *Department of Energy Science, Sungkyunkwan University, Suwon 16419, Republic of Korea*

[b] *Center for Integrated Nanostructure Physics (CINAP), Institute for Basic Science (IBS), Sungkyunkwan University, Suwon 16419, Republic of Korea.*

whquddnr@g.skku.edu,leeyoung@skku.edu,

Substitutional impurity doping in two-dimensional (2D) transition metal dichalcogenides (TMDs) plays a profound role on tuning their physical properties. However, it is still challenging to achieve desirable doping concentration with simplified route. Here, we report widely tunable substitutional metal doping in 2D TMDs via one-step chemical vapor deposition (CVD) based on liquid-phase precursor mixing. The key to obtain highly controllable doping concentration with easiness is to choose appropriate metal precursors owing to their high variance of doping abilities depending on their chemical structure. By varying the ratio of dopant and host precursors, physical properties of host 2D TMDs have been successfully modulated. We further demonstrated that liquid-phase mixing method can be extended to co-doping process, in which two-different impurities are incorporated into host materials, highlighting the versatility of the method.

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Single-crystal growth of transition metal dichalcogenide films on atomic sawtooth Au surface

Soo Ho Choi [a,b]

[a]*Center for Integrated Nanostructure Physics (CINAP), Institute for Basic Science (IBS), Suwon 16419, Republic of Korea.*
[b]*Sungkyunkwan University, Suwon 16419, Republic of Korea.*
soohochoi@skku.edu

Two-dimensional (2D) layered materials such as graphene, transition metal dichalcogenides (TMDs), and hexagonal boron nitride (hBN) have attracted attention due to their distinctive physical and chemical properties. Therefore, many applications such as high-performance field-effect transistors, atomically thin pn diodes, and Coulomb drag transistors have been investigated. However, such applications are currently only available with a lateral size of up to a few tens of micrometers. Therefore, large-scale synthesis of homogeneous 2D films is highly required for industrialization. While the wafer-scale single-crystal monolayer graphene and hBN films have been successfully grown [1-3], an ideal growth platform for diatomic TMD films has not been established to date. Herein, we report the single-crystal growth of TMD films by using atomic sawtooth Au substrates. The atomic sawtooth Au surface, which has periodic atomic step-edges and terraces, is simply prepared by one-step solidification of liquid Au. The atomic step-edges provoke the anisotropic adsorption energy of the TMD cluster, eventually leading to the growth of coherently aligned TMD grains over the whole region. The aligned TMD grains are merged without producing grain boundaries and form the single-crystal film. Growth using the atomic sawtooth gold surface as a universal growth template is demonstrated for several TMD monolayer films, including WS_2, WSe_2, MoS_2, the $MoSe_2/WSe_2$ heterostructure, and $W_{1-x}Mo_xS_2$ alloys. This strategy provides a general avenue for the single-crystal growth of diatomic van der Waals heterostructures on a wafer scale, to further facilitate the applications of TMDs in post-silicon technology.

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Multifunctional CNT films: Scalable synthesis and applications

DM Hu, ZY Yong, YY Zhang, HH Jin and Qingwen Li

Advanced Materials Division, Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences, Suzhou 215123, China

E-mail: qwli2007@sinano.ac.cn

Abstract

Due to their unique structures and superior mechanical, electrical, and other physical properties, carbon nanotubes (CNTs) have shown great potential as building blocks for a variety of novel high-performance materials. CNT films, which can be synthesized via chemical vapor deposition (CVD) methods as well as wet processing approaches, have been proven to be promising for using as composite reinforcements, electric conductors, thermal management materials, etc. Especially, high-strength and highly conductive CNT films prepared via floating catalyst chemical vapor deposition (FCCVD) have gained increasing interests due to its low-carbon synthetic approach for advanced materials, as well as its great potential in fabrication of multifunctional devices for wearable electronics and energy storage applications. This talk will introduce our recent progress in large-scale preparation of low-cost and high-performance CNT films and application development in smart wearable devices, personal outdoor protection, thin-film energy devices and electromagnetic shielding etc.. Finally, I will give some comments on the challenges and perspectives toward the future of the CNT film.

The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

Parallel Symposia Program & Abstract

Macromaterials

Parallel Symposia **MACROMATERIALS @ Chemistry Building # 330118**

Thursday, JUNE 23rd, 2022

		Chair: Changsik Song (Sungkyunkwan University)
14:30-15:00	P-Ma-I1	**John Bulmer** (Air Force Research Laboratory, USA) *Forecasting CNT Diameter and Yield in Floating Catalyst CVD*
15:00-15:30	P-Ma-I2	**Bon-Cheol Ku** (KIST, Korea) *Structure-controlled ultrahigh performance carbon nanotube fibers*
15:30-15:40	Short break	
		Chair: Bon-Cheol Ku (KIST)
15:40-16:10	P-Ma-I3	**Changsik Song** (Sungkyunkwan University, Korea) *Green Malleable Thermoset Polymers for Highly Conductive Thermal Interface Materials with Ultra-Low Thermal Contact Resistance*
16:10-16:40	P-Ma-I4	**Alexander Balandin** (University of California, USA) *Graphene composites for thermal management and electromagnetic interference shielding*
16:40-17:00	P-Ma-C1	**Cristina Madrona** (IMDEA, Spain) *Intercalation of Carbon Nanotube Yarns with Acceptor Dopants*

Friday, JUNE 24th, 2022

		Chair: Chang-Soo Han (Korea University)
13:15-13:45	P-Ma-I5	**Milo Shaffer** (Imperial College London, UK) *Wet-spinning Carbon and Inorganic Nanotube Fibres*
13:45-14:15	P-Ma-I6	**Philippe Poulin** (CNRS Bordeaux, France) *Super flexibility of graphene oxide: a key for processing graphene based macromaterials*
14:15-14:25	Short break	
		Chair: Seunghyun Baik (Sungkyunkwan University)
14:25-14:55	P-Ma-I7	**Geoff Wehmeyer (**Rice University, USA) *Axial thermal conductivity and thermal diffusivity measurements in high-conductivity aligned wet-spun carbon nanotube fibers*
14:55-15:25	P-Ma-I8	**Dmitry Rybkovskiy** (Skolkovo Institute of Science and Technology, Russia) Structure of Phosphorus formed inside carbon nanotubes
15:25-15:45	P-Ma-C2	**Bharath Natarajan** (ExxonMobil Research and Engineering, USA) *Fundamentals of resin infiltration into carbon nanotube rich articles*

Forecasting CNT Diameter and Yield in Floating Catalyst CVD

J. Bulmer[1,2], A. Sloan[3*], M. Glerum[4*], J. Carpena-Núñez[1,2], R. Waelder[1,2], T. Cherukuri[5], A. Boies[4], M. Pasquali[3], R. Rao[1], B. Maruyama[1]

1 Air Force Research Laboratory, AFRL/RX, Wright-Patterson Air Force Base, Ohio 45433
2 UES, Inc. 4401 Dayton Xenia Rd, Dayton, OH 45432
3 The Smalley-Curl Institute, Rice University, Houston, Texas 77005, United States
4 Department of Engineering, University of Cambridge, Cambridge, CB2 1PZ, UK
5 Applied NanoFluroesence, 5252 Westchester, Ste 150, Houston, Texas 77005
john.bulmer.2.ctr@afresearchlab.com

Robustly controlling single-wall carbon nanotube (SWCNT) diameter, yield, and residual iron content in floating catalyst chemical vapor deposition (FC-CVD) is critical for practical applications; no established theory generalizable to all FC-CVD reactors exists that predicts these production properties or their interrelated relationships. Here, we show validated, multivariate statistical modeling that robustly forecasts SWCNT diameter, yield, and residual iron content by systematically experimenting with an extensive variety of fundamental FC-CVD reactor parameters to include: CO_2, H_2, and Ar flowrates; fuel flowrate; added H_2O; ferrocene and sulfur-promotor concentration; reactor temperature (covering temperatures with solid and liquid floating catalyst); quartz reactor tube age; and carbon precursor source. SWCNT diameter is measured across three Raman wavelengths and iron content is gauged by a contactless electromagnetic permeability probe. We will discuss a precursor vaporizer and other reactor hardware improvements that improve the reactor repeatability from our previous studies. Enabling generalizability between FC-CVD reactors, this multivariate statistical modeling is a new paradigm of FC-CVD reactor control; it accounts for interaction between reactor input factors, system noise, and other non-linear responses. This multivariate statistical approach is accomplished by conducting hundred of experiments intelligently selected by machine learning algorithms, made possible by the Autonomous Research System (ARES), an open-source operating system for closed-loop automated experimentation being developed at Air Force Research Laboratory (AFRL) under Benji Maruyama.

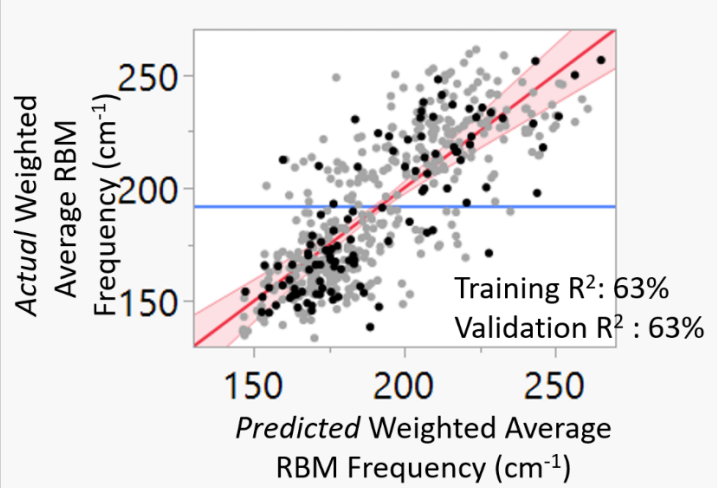

Fig 1. Relationship between the actually measured weighted average RBM diameter and the value the multivariate statistical model predicts, as a function of FC-CVD parameters. Validation (in black) is accomplished by incorporating datasets not used in model training.

Structure-controlled ultrahigh performance carbon nanotube fibers

Dongju Lee[a], Seo Gyun Kim[a], Bon-Cheol Ku[a]*

[a]Institute of Advanced Composite Materials, Korea Institute of Science and Technology (KIST); Wanju 55324, Republic of Korea

**cnt@kist.re.kr*

Carbon nanotube (CNT) fibers have been considered as the high-performance fibers; however, their mechanical, electrical, and thermal properties are much lower than the theoretical values [1]. To realize CNT fibers with high-performance bulk properties, a few parameters including CNT length, alignment [2], densification, cross-linking [3,4] and morphology [5] should be considered and optimized. Recently, we explored the structural orientation and morphology of wet-spun fibers and connected them with the fiber properties [6]. In addition, we proposed a method for forming multidimensional nanostructures by thermal treatment of highly aligned CNT fibers to increase the interactions between graphitic layers through CNT collapse, and coalescence [5]. The resulting fibers have an unprecedented combination of high tensile strength (6.57 GPa), modulus (629 GPa), thermal conductivity (482 W/m·K), and electrical conductivity (2.2 MS/m), thereby overcoming the limits associated with conventional synthetic fibers. In this presentation, I will discuss structure and properties relationship of ultrahigh performance CNT fibers.

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Green Malleable Thermoset Polymers for Highly Conductive Thermal Interface Materials with Ultra-Low Thermal Contact Resistance

Inhwan Cha,[a] Taehun Kim,[b] Seunghyun Baik [b] and Changsik Song*,[a]

[a]Department of Chemistry, Sungkyunkwan University, Suwon, Gyeonggi 16419, Republic of Korea. [b]School of Mechanical Engineering, Sungkyunkwan University, Suwon, Gyeonggi 16419, Republic of Korea.

songcs@skku.edu

As the degree of integration of electronic devices becomes increasingly sophisticated, the development of good heat control materials is highly demanded. However, the trade-off between thermal conductivity and thermal contact resistance is considered to be a stumbling block in the development of excellent thermal interface materials (TIMs). In this work, we introduced malleable network (thermoset) polymers as a host material for a highly conductive TIM while effectively lowering the thermal contact resistance. In general, mechanically robust thermoset polymers exhibit good thermal conductivity, but often produce poor contact at the interface. To address this problem, we used dynamic covalent chemistry to impart malleability to thermoset polymers, giving rise to excellent thermal contact. Our malleable thermoset polyurethanes and polyesters were synthesized from biomass-derived resources via a facile, solvent-free ball milling process. Dynamic mechanical thermal and stress relaxation analyses of the thermoset polymers indicated that they possess typical characteristics of malleable thermosets or vitrimers, such as constant crosslink density and Arrhenius-like reduction in viscosity at elevated temperatures (> T_v, topology freezing transition temperature), which can be attributed to the dynamic covalent exchange reactions. Highly conductive composites were prepared in a similar way by incorporating Ag flakes and Ag-nanoparticle-decorated multiwalled carbon nanotubes in the polymer matrix. The highly dispersed composite materials showed high thermal conductivity through laser flash analysis (LFA). Remarkably, the initial thermal resistance (R_t = 516 mm^2 K W^{-1}) decreased significantly to 36.2 mm^2 K W^{-1} at the temperature above T_v, which remained well even after cooling to room temperature. Our approach using a malleable thermoset polymer host is easy and scalable, preparing high-efficiency TIMs for future thermal management.

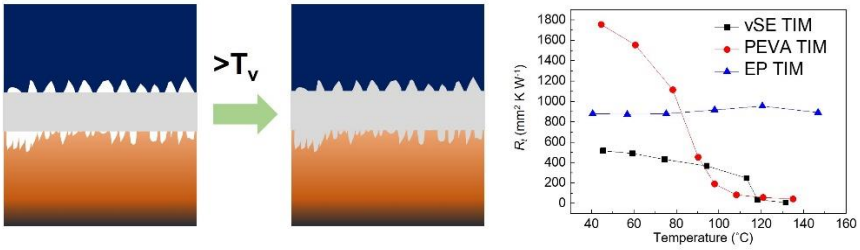

Fig 1. Schematics of malleable TIM (vSE TIM) and significantly decreased total thermal resistance (R_t) at increased temperatures.

Graphene composites for thermal management and electromagnetic interference shielding

Alexander A. Balandin
Department of Electrical and Computer Engineering
Materials Science and Engineering Program
University of California, Riverside, USA
balandin@ece.ucr.edu

The discovery of unique heat conduction properties of graphene [1] motivated research focused on the thermal conductivity of graphene, few-layer graphene, and composites with graphene fillers [2]. Recent developments suggest that the large-scale practical applications of graphene can be expected specifically in thermal management – thermal interface materials, thermal coatings, and related [3-4]. On the other side, it has been demonstrated that graphene composites are efficient electromagnetic interference shielding materials – they can reflect and absorb electromagnetic energy efficiently even at a low loading fraction of graphene, below the percolation limit, while remaining electrically insulating [5]. The dual function of graphene composites and the possibility of independent control of their electrical and thermal properties provides extra benefits for practical applications. The general class of the van der Waals layered materials is not limited to two-dimensional materials such as graphene or transition metal dichalcogenides, which exfoliate into atomic planes. There exist van der Waals materials with one-dimensional motifs in their crystal structure, such as transition metal trichalcogenides, which exfoliate into needle-like atomic chains [6-7]. The exceptional properties of such low-dimensional materials and their composites will also be discussed.

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INTERCALATION OF CARBON NANOTUBE YARNS WITH ACCEPTOR DOPANTS

Cristina Madrona[1,2]

[1] *IMDEA Materials, Spain.* [2] *Department of Applied Physics, UAM, Spain*

cristina.madrona@imdea.org

One of the most promising architectures to study and exploit the axial properties of CNTs is as macroscopic yarns, where CNTs are predominantly aligned and form extended bundles. Improvements in the control of alignment, packing, and polydispersity of constituent CNTs in macroscopic yarns offer an attractive library of highly crystalline CNT-based materials.[1,2]

In this work, we present recent results on the preparation of intercalated CNT fibers with different electron acceptors, both in collapsed and rounded DWCNTs. We present thorough characterization of the crystal structure by HRTEM and wide-angle x-ray scattering (WAXS) measurements showing intercalation throughout the entire macroscopic CNT fibers, with long-range order of intercalant in some locations and staging in the case of collapsed DWCNTs (see Figure 1). To this regard, the presentation also discusses the different possible sites of intercalant in CNT fibers, for instance, in between adjacent CNTs, encapsulated inside the inner CNT cavity, etc. Using previous results,[3] we quantify charge transfer through Raman spectroscopy. Next, we present an increase of nearly one order of magnitude in the electrical properties of intercalated CNT fibers, stable in ambient air and at considerably high temperatures. Combined with tensile properties in the high-performance range, these intercalated fibers are attractive as lightweight, tough conductors.

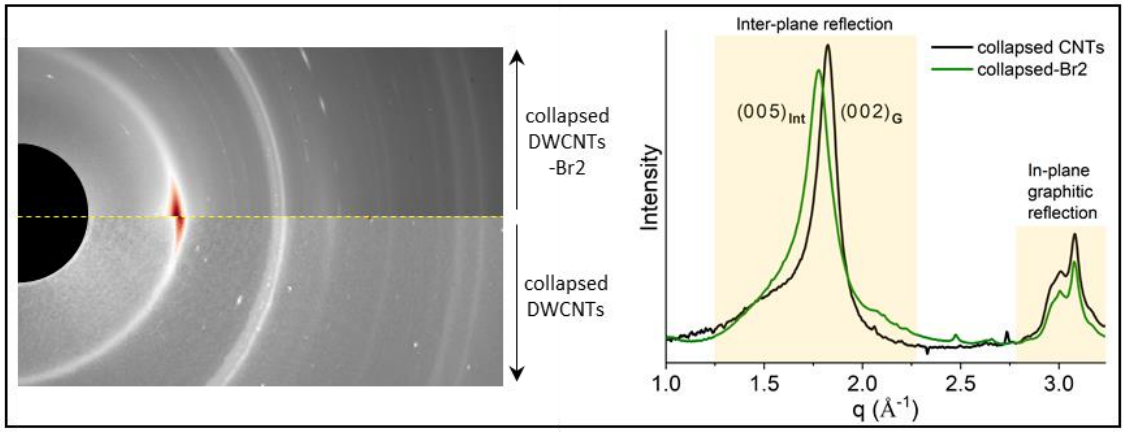

Figure 1. WAXS 2D (left) and integrated (right) patterns of Br_2-intercalated collapsed DWCNT yarns.

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Wet-spinning Carbon and Inorganic Nanotube Fibres

Shaffer MSP
Imperial College London
Department of Materials Science, South Kensington, SW7 2AZ
m.shaffer@imperial.ac.uk

As 1D materials with high intrinsic strength and stiffness, nanotubes are promising building blocks for the next generation of structural and multifunctional fibres. Carbon nanotubes (CNTs) are an obvious target constituent, but present challenges both in processing, due to their intractability, and in characterization, due to the high optical absorbance, low X ray scattering cross section and polydispersity. Imogolite nanotubes (INTs) are an inorganic analogue, with complementary properties and potential applications. They offer an opportunity to observe the assembly of nanotubes into fibres, more easily, using polarised optical microscopy (POM) and X ray scattering (XRS). In contrast to CNTs, INTs are optically transparent and can be synthesised at low temperature to produce monodispersed feedstocks in water.

The first pure INT fibres have been produced by wet-spinning and analysed to improve the nanotube wet spinning process more generally. The importance of NT aspect ratio, spinneret design, and coagulation process have all been considered. Interestingly, the dry fibres show an unexpected relationship between structural and mechanical properties: less aligned fibres are stiffer and stronger. It is proposed that jamming of the nanoscale rods is required to efficiently transfer load in the relatively loosely packed fibres. The inter-nanotube interaction can be manipulated by varying humidity. Dense, composite INT fibres can be prepared using compatible polyvinyl alcohol matrices. Here, the conventional dependence on INT orientation is returned, reinforcing the polymer. More intriguing, these fibres show a degree of self-healing, at unusually high absolute mechanical performance

Building on this knowledge, CNT fibres were spun from reduced “nanotubide” solutions, using an optimal degree of charging. In this case, a reactive, charge quenching coagulant can be used in order to form a stable proto fibre which can be collected and densified, depending on the reactivity of the coagulant and the coagulation time to achieve the best fibre properties, both mechanical and electrochemical.

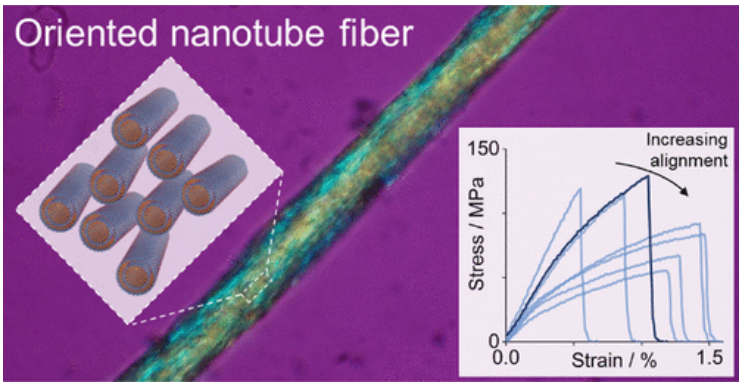

Figure Polarized optical micrograph of a pure imogolite nanotube fibre (diameter ~20 microns), a schematic atomic structure, and the mechanical response

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Super flexibility of graphene oxide: a key for processing graphene based macromaterials

Philippe Poulin

CNRS Bordeaux, Centre de Recherche Paul Pascal, 115 avenue Schweitzer, 33600 Pessac, France.

Philippe.poulin@crpp.cnrs.fr

Bending of atomic monolayers is of great technological and scientific significance because continuum mechanics of thin plates is not applicable down to one atom thick layers. In spite of numerous numerical and theoretical studies, experimental measurements of the bending rigidity of one atom thick layer remain a challenge. We report in this work, experimental measurements of the bending rigidity of graphene oxide (GO) monolayers. Using X-ray synchrotron radiations, we show that GO layers in solution display thermal undulations that are flattened by viscous forces when the solution is sheared (Fig. 1). This phenomenon allows for quantitative measurements of the bending rigidity. Disregarding its wavelength dependence, the bending rigidity of GO was found to be $2kT$, with kT the thermal energy[1]. This very low value compares with the bending rigidity of liquid systems, such as biological phospholipid bilayers. However, GO is a solid and very stiff material; meaning that the wavelength dependence of its bending rigidity cannot be neglected. We discuss in this presentation the re-interpretation of earlier results by considering this dependence. The conclusions are changed from a quantitative point of view, but the conclusion that GO is a superflexible material remains valid. Superflexibility of GO is a unique feature to develop bendable electronics, films, coatings and fibers. The combination of properties of GO allows for flexibility in processing along with robustness in the fabricated structure.

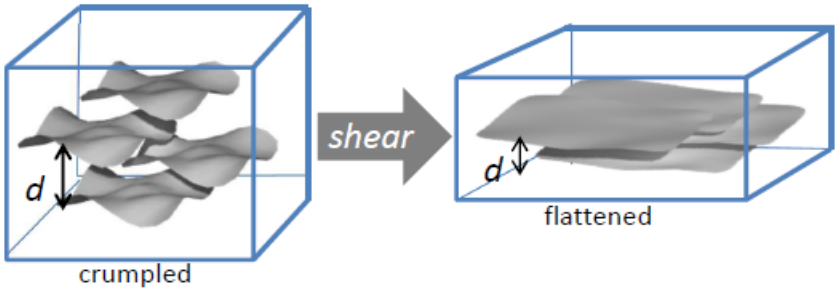

Fig 1. GO sheets are highly flexible. They undulate in response to thermal fluctuations when suspended in a solution. These undulations are flattened under shear. The spacing between the sheets varies as a function of shear rate.

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Axial thermal conductivity and thermal diffusivity measurements in high-conductivity aligned wet-spun carbon nanotube fibers

G. Wehmeyer
William Marsh Rice University
6100 Main St, Houston TX 77005
Geoff.wehmeyer@rice.edu

The electrical conductivity, thermal conductivity, and yield strength of wet-spun aligned carbon nanotube (CNT) fibers has showed dramatic improvement in the past two decades, opening new applications for CNT fibers as high-strength, lightweight electrical conductors with improved axial thermal heat spreading. Prior measurements have shown that the axial thermal conductivity (k_a) of high-quality CNT fibers can reach $400-600$ $\mathrm{W/m.K}$ at room temperature, and can be tuned by controlling the dopant concentration, tube length, and degree of alignment [1-3]. Interestingly, recent increases in tube length that were successful in enhancing σ have not been correlated with increased k_a [4], suggesting that intrinsic phonon-phonon or phonon-impurity scattering within the tube may be more important than interface resistances in impeding phonon transport. This presentation focuses on measurements of the axial thermal conductivity k_a and axial thermal diffusivity α_a for high-electrical conductivity (>1 MS/m) CNT fibers. Fig. 1(a) shows a CNT fiber that is suspended between two epoxy pads and Joule-heated with an electrical current. In our steady-state resistance thermometry method [5], we use dc currents and use the spatially-averaged fiber temperature rise as a function of the Joule heating power (Fig. 1(b)) to extract k_a. Our three-omega method shown in Fig. 1(c) uses time-periodic electrical heating and lock-in detection of frequency dependent heating to determine α_a. We use these measurements to study the effects of doping and tube length on axial thermal transport in CNT fibers.

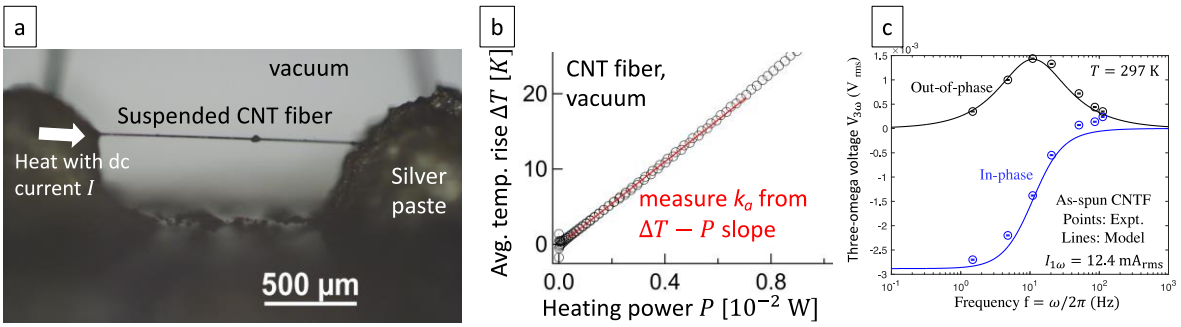

Fig 1. Measurements of CNT fiber axial thermal conductivity k_a and axial thermal diffusivity α_a. **(a)** We suspend CNT fibers in vacuum, Joule heat the fiber using electrical currents, and measure the average fiber temperature rise ΔT using resistance thermometry. **(b)** Measured steady-state data for as-spun CNT fibers with $k_a = 390 \pm 60$ $W/m.K$; Data from Taylor, **Wehmeyer**, et al. *Carbon* 171, 689 (2021). **(c)** Three-omega electrothermal measurements of suspended CNT fibers using ac currents enables determination of $k_a = 370 \frac{\mathrm{W}}{\mathrm{m.K}}$ and axial thermal diffusivity $\alpha_a = 1.3 * 10^{-4}$ $\mathrm{m^2/s}$.

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Structure of Phosphorus formed inside carbon nanotubes

Dmitry Rybkovskiy[1,2], Victor Koroteev, Anthony Impellizzeri, Anna Vorfolomeeva, Evgeny Gerasimov, Alexander Okotrub, Andrey Chuvilin, Lyubov Bulusheva, Chris Ewels

[1]Skolkovo Institute of Science and Technology, Bolshoy Boulevard 30, bld. 1, 121205 Moscow, Russia
[2]Prokhorov General Physics Institute of the Russian Academy of Sciences, Vavilov street 38, 119991 Moscow, Russia
D.Rybkovskiy@skoltech.ru

Phosphorus is well known for its wide structural diversity, which is also displayed at the nanoscale. This property has recently led to extensive studies of 1D-phopshorus allotropes, primarily through confinement within carbon nanotubes. In our current study we have filled intermediate diameter carbon nanotubes (1.6-2.9nm) with phosphorus. Via detailed experimental characterization (notably with HRTEM and Raman), coupled to extensive DFT studies of structure, energetics and vibrational behavior, we are able to unambiguously identify and characterize red-phosphorus chain structures in the nanotubes. As a result of the study, we resolve much of the literature complexity, showing that red-P based chain structures are in fact the stable preferred form in all nanotube cavities above ~1nm (in smaller diameter tubes these chains can no longer fit and hence intrinsically less stable structures such as zigzag chains form instead). We unify two structurally related chains models (P8]P2 and fibrous Phosphorus) in terms of a new interstitial defect model and identify a specific Raman band at 254 cm^{-1} as the characteristic signature for cross-linking between the chains.

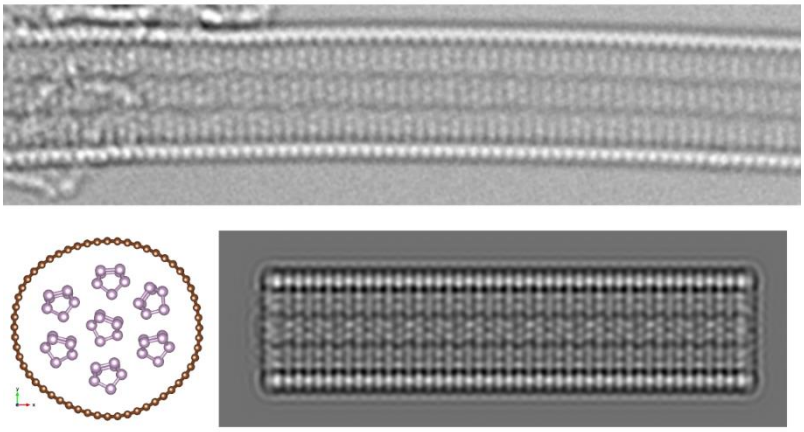

Fig 1. Comparison of experimental and simulated HRTEM images of phosphorus formed inside carbon nanotube

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Fundamentals of resin infiltration into carbon nanotube rich articles

Bharath Natarajan[§], *Robert Colby*[§], *Thomas Sun*[§], *Peter Jacobs*[§]

[§]*Corporate Strategic Research, ExxonMobil Research and Engineering, Annandale, NJ 08801 USA*

bharath.natarajan@exxonmobil.com

A key step towards realizing the promise of macroscopic carbon nanotube (CNT) articles or preforms (sheets, yarns, fibers) in high-performance structural applications is polymer infiltration into the porous CNT structure. The polymer improves stress transfer between CNTs, enhances multi-axial performance and promotes long-term material integrity. However, infiltration is often found to be sub-optimal - a significant impediment to the scaling and adoption of CNT-article composites that has thus far received little systematic attention. In this work, a unique combination of inverse gas chromatography (IGC) and a statistical thermodynamic model is used to accurately quantify the energetic driving force for infiltration into CNT articles for the first time. This is measured to have a very low value. Using gas chromatography-mass spectroscopy, IGC analysis and electron microscopy, this low energy is found to result from near-complete surface coverage by non-graphitic pyrolysis byproducts. The surface energy is improved by plasma and thermal treatment as confirmed by IGC analysis. The effects of the surface treatment and modifications to the porous structure on the infiltration rate of model liquids are studied by optical imaging. Accurate surface energy measurements and image analysis are coupled to shed light on the dependence of infiltration rate and extent on critical parameters such as surface tension, viscosity and microstructure. From these validated models of resin infusion, a range of target resin properties are identified for improved infilling into CNT articles. Resins are formulated or selected with these property targets in mind and evaluated for ease and quality of infusion.

The 22nd International Conference on the Science and Applications of Nanotubes and Low-Dimensional Materials

List of Poster Presentation

Poster Session

Poster Session	Poster No.	Name	Affiliation	Title	Participant
P1	P1-I-03	Ileana FLOREA	LPICM, CNRS	In situ ETEM studies of Fe catalyst NPs formation under molecular or radicals/activated hydrogen environments for the growth of SWCNTs	In-person
P1	P1-I-04	Izaac Mitchell	Institute for Basic Science	The Role of Graphitic Bowls in Temperature Dependent Fullerene Formation	In-person
P1	P1-I-06	Dmitry Krasnikov	Skolkovo Institute of Science and Technology	High-Quality Graphene Using Boudouard Reaction	In-person
P1	P1-I-07	Dmitry Krasnikov	Skolkovo Institute of Science and Technology	Joint effect of ethylene and toluene on carbon nanotube growth	In-person
P1	P1-I-08	Keigo Otsuka	The University of Tokyo	Universal map of kinetic selectivity in catalytic growth of carbon nanotubes from carbon feedstocks and etching agents	In-person
P1	P1-I-09	Keigo Otsuka	The University of Tokyo	Effects of additionally supplied carbon or oxidants on speed, incubation, and lifetime of carbon nanotube growth from ethanol	In-person
P1	P1-I-11	Xiao Kong	Institute for Basic Science	Spiral Growth of Adlayer Graphene	In-person
P1	P1-I-12	Yifan Zhao	Ulsan National Institute of Science and Technology	Structural Transition C60 Bulk under High Temperature and High Pressure and Diagram of new Carbon Materials	In-person
P1	P1-I-13	Lu Qiu	Institute for Basic Science (IBS)	Carbon Chain Formation at the Carbon Nanotube-Catalyst Interface	In-person
P1	P1-I-14	Ji Hong Park	Korea Institute of Science and Technology	Effects of Sulfur Concentration and Catalyst Precursor Type on Carbon Nanotube Synthesis using Deep-Injection Floating-Catalyst Chemical Vapor Deposition	In-person
P1	P1-I-15	Seoyoung Jang	Korea Carbon Industry Promotion Agency	Carbon Nanotube Synthesis Using Fe-Mo/MgO Catalyst with Different Metal Ratio	In-person
P1	P1-I-16	Zain Mehdi	Sejong University	Superior field emission characteristics of heteroatom-doped MWCNTs fabricated through electric arc discharge	In-person
P1	P1-I-17	Chunghun Kim	Gachon university	High concentration boron doping of graphene by arc discharge and its electrochemical applications	In-person
P1	P1-I-19	Hyeongyun Song	Pusan national university	Bayesian optimization of the wet impregnation of catalysts for the synthesis of carbon nanotubes	In-person
P1	P1-I-20	Alisa Bogdanova	Skolkovo Institute of Science and Technology	Promoters influence on the single-walled carbon nanotube synthesis	In-person
P1	P1-I-21	Dong Hwan Kim	Pusan National Unversity	Reducing variability in the synthesis of carbon nanotubes by chemical vapor deposition using impregnated catalysts	In-person
P1	P1-I-22	Sang Su Shin	Pusan National University	Engineering Thiele modulus for a high-yield synthesis of carbon nanotubes in a fluidized bed reactor	In-person
P1	P1-I-23	Clascidia Furtado	Nuclear Technology Development Center	Molecular insights into the production of few-layer graphene in N-Cyclohexylpyrrolidone + water mixtures	In-person
P1	P1-I-24	Myungwoo Choi	Korea Advanced Institute of Science and Technology	Improved Crystallinity of Graphene Grown on Cu/Ni (111) through Sequential Heat Treatment	In-person
P1	P1-I-25	Joon Young Cho	Korea Electrotechnology Research Institute (KERI)	Less defective and metal ion-free GO nanosheets with extraordinary thermal-stable in air	In-person
P1	P1-I-27	Hayoung Ko	Sungkyunkwan University	Toward non-gas-permeable hBN film growth on smooth Fe surface	In-person
P1	P1-I-28	Jaegyun Im	Pusan National University	Analysis of dispersion state of carbon nanotubes in m-cresol	In-person
P1	P1-I-29	Etienne Gaufrés	CNRS	1D Heterostructures Based on Nanotube Templates: Confinement of 6T Molecules Inside BNNT For Highly Polarized Light Emission	In-person
P1	P1-I-30	Sungwoo Lee	Sungkyunkwan University	Au Nanoframes with Nanoporous Structure	In-person
P1	P1-I-31	Jongdoo Lee	Sungkyunkwan University	Zinc on microporous organic nanoparticles as heterogeneous catalysts for biodegradable polycaprolactone synthesis	In-person
P1	P1-I-32	Sang Hyun Ryu	Sungkyunkwan university	Au Clusters and Nanoparticles on Nanoparticulate CeO2 Hollow Spheres for the Selective Synthesis of Biomass-derived Building Blocks	In-person
P1	P1-I-33	SUN BU LEE	Sungkyunkwan University	Aliphatic β-Sulfido SuFEx Hubs via Organo-Superbase Catalysis "onwater"	In-person
P1	P1-V-01	Xiaoming Ma	Zhejiang University	Carbon nanotube based in situ liquid-cell TEM for atomic scale imaging of liquid-phase chemical reactions under nanoconfinement	Virtual
P1	P1-V-02	Jue Wang	Yancheng Institute of Technology	Growth of single-walled carbon nanotubes from size-selected Fe clusters	Virtual
P1	P1-V-03	Hisayoshi Oshima	Nagoya University	Direct dispersion in solvent of single-walled carbon nanotubes grown by floating-catalyst chemical vapor deposition	Virtual
P1	P1-V-04	Thomas blin	Institut de Chimie Moléculaire et des Matériaux d'Orsay	Bimetallic carbides as a catalyst for the growth of single-walled carbon nanotubes	Virtual
P1	P1-V-05	HAOLU LIN	Okayama University	Synthesizing Small-Diameter Single-walled Carbon Nanotubes by Floating Catalyst Chemical Vapor Deposition	Virtual

Poster Session

P1	P1-V-06	Muxiao Li	Rice University	The Effect of Iron Flow Rate and Sulfur/Iron Molar Ratio on CNT Synthesis by Floating Catalyst Chemical Vapor Deposition (FCCVD)	Virtual
P1	P1-V-07	Yoshiya Kishibe	University of Tsukuba	CNT growth and carbon transfer manner evaluated from 13C isotope labeling	Virtual
P1	P1-V-08	Wenqing Yan	Peking University	Diameter manipulation of carbon nanotubes in floating catalyst chemical vapor deposition using bimetallic catalysts	Virtual
P1	P1-V-09	Xue Zhao	Peking University	Growth of horizontally aligned semiconducting single-walled carbon nanotube arrays using carbon monoxide as carbon feedstock	Virtual
P1	P1-V-10	Shaochuang Chen	Peking University	Single-walled carbon nanotubes synthesized by laser ablation from coal	Virtual
P1	P1-V-11	Guohai Chen	National Institute of Advanced Industrial Science and Technology (AIST)	Microplasma-based multi-step chemical vapor synthesis reactor for structure-controlled synthesis of single-walled carbon nanotubes	Virtual
P1	P1-V-12	LIU YUANJIA	Osaka university	Kite-growth of long, aligned carbon nanotubes from non-metallic growth seeds	Virtual
P1	P1-V-13	Mengyue Wang	Osaka University	Effect of CO2 in high temperature SWCNT growth from solid carbon growth seeds	Virtual
P1	P1-V-14	Han Li	Karlsruhe Institute of Technology	Sorting single-chirality enantiomers of single-wall carbon nanotubes by surfactant-assisted aqueous two-phase extraction	Virtual
P1	P1-V-15	Hironori Ogata	Hosei University	Synthesis and electrocatalytic properties of Pt nanoparticles on carbon nanotubes composites	Virtual
P1	P1-V-16	WEIHUA WANG	Ulsan National Institute of Science and Technology	Mechanism of diamond epitaxial nucleation on Ir substrates	Virtual
P1	P1-V-17	Der-Yuh Lin	National Changhua University of Education	Controllable Growth and Characterization of large-area SnSe2 and SnSe films on Silicon substrate by Chemical Vapor Deposition	Virtual
P1	P1-V-18	CHEN PENGFEI	Waseda University	Understanding and controlling the gas-phase pyrolysis of hydrocarbon for efficient carbon nanotube synthesis	Virtual
P2	P2-I-01	Ahmed ANDALOUCI	NAWATECHNOLOGIES	Vertically Aligned Carbon Nanotube fibers synthesised on porous substrates.	In-person
P2	P2-I-02	John Texter	Eastern Michigan University	0D + 1D = 2D –Heterogeneous Electrodes by Electrospinning	In-person
P2	P2-I-03	Nikita Nekrasov	National Research University of Electronic Technology	Carbon nanotube phototransistors gated by green fluorescent protein	In-person
P2	P2-I-05	Jan Gotthardt	University of Heidelberg	Molecular Doping of Bottom-Gate/Top-Contact Nanotube Network Field-Effect Transistors for Flexible Electronics	In-person
P2	P2-I-07	Huanyu Zhou	Seoul National University	Intrinsically Stretchable Two-Dimensional-Contact Electrodes for Highly-Efficient Organic Light-Emitting Diodes	In-person
P2	P2-I-08	Sayed Zafar Abbas	Sejong University, South Korea	High-performance CNT paste emitters generate high current density by improving cohesion and adhesion strength through silicide formation	In-person
P2	P2-I-09	Martin Hartmann	Chemnitz University of Technology	Interface preprocessing for Contact Formation of Dispersion-based Carbon Nanotube Field-Effect Transistors	In-person
P2	P2-I-10	bdurrahman Ali El Yum	Nanomaterials for Optoelectronics Group	Trion Electroluminescence from Static p-n Junctions of Electrolyte-Gated (6,5) Single-Walled Carbon Nanotube Networks	In-person
P2	P2-I-11	Antonia Kagkoura	National Hellenic Research Foundation	Chemically modified carbon nanostructures as carriers of enhanced qualities for fabrics performing under critical operational conditions	In-person
P2	P2-I-12	Anastasiia Kudriavtseva	National Research University of Electronic Technology	Controlling carbon nanotube light-inducing gating by green fluorescent protein via chromophore fluorescence quenching	In-person
P2	P2-I-13	Jeronimo Terrones	University of Cambridge	Direct-spun CNT textiles and composites for high-performance ultra-wide bandwidth electromagnetic shielding	In-person
P2	P2-I-14	Philipp Kloza	University of Cambridge	Mechanism of Alignment Enhancement of CNT Fibres by AC Electric Fields	In-person
P2	P2-I-15	Sujin Cha	Korea Advanced Institute of Science and Technology	Improved Electrical and Mechanical Properties of Self-Planarized Graphene Liquid Crystalline Fibers by Hydration	In-person
P2	P2-I-16	Shinichiro Matano	Keio University	Polarized and Broadband Light Emission from an Electrically Driven Aligned Carbon Nanotube Film	In-person
P2	P2-I-17	Shohei Chiashi	The University of Tokyo	One-dimensional electrical transport in single-walled carbon nanotube two-dimensional thin films	In-person
P2	P2-I-18	YUI SHIMURA	Keio University	High-performance, high-productivity on-chip light-emitting devices using etching and deposition method graphene	In-person
P2	P2-I-20	Gyeong-Tak Go	Seoul National University	Synaptic Plasticity of Ion-gel Gated Monolayer Graphene Synaptic Transistor	In-person
P2	P2-I-21	Ilya Novikov	Skolkovo Institute od Science and Technology	Multifunctional elastic TPU nanocomposites with extremely low SWCNT concentrations for soft electronics	In-person
P2	P2-I-23	Jung Hoon Kim	Korea Electrotechnology Research Institute	Rational oxidation and reduction of SWCNTs for electrochemical applications	In-person
P2	P2-I-24	Yongjun Kim	Sungkyunkwan University	Highly reversible nanocomposite strain sensors incorporating silver nanoflowers for human motion monitoring	In-person
P2	P2-I-25	Geunwoo HWang	Sungkyunkwan University	Orbital Gating Driven by Giant Stark Effect in Tunneling Phototransistors	In-person
P2	P2-I-26	Phu Le	Institute for Basic Science (IBS)	Ohmic-contact multi-layered tungsten diselenide (WSe2) field-effect transistor via V-doped WSe2 intermediated layers	In-person

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P2	P2-I-27	Anir Syahmi bin Sharbiri	Sungkyunkwan University	Synthesis and Characterization of Light-Emitting Ti2N Quantum Dots	In-person
P2	P2-I-28	Phuc Do	Sungkyunkwan University	Type II heterostructure based on 2D Graphdiyne toward high responsivity, broadband photodetectors	In-person
P2	P2-I-29	Jihyun Kim	Sungkyunkwan University	Solution-Processed Van der Waals Heterostructure for Low Power Optoelectronics	In-person
P2	P2-I-30	Anastasia Goldt	Skolkovo Institute of Science and Technology	Highly Efficient Doping of Single-Walled Carbon Nanotubes	In-person
P2	P2-I-31	Chanwoo Lee	Korea Advanced Institute of Science and Technology	Ti3C2Tx MXene Film with High Alignment and Ambient Stability for Electromagnetic Interference Shielding	In-person
P2	P2-I-32	Wooseon Choi	Sungkyunkwan University	Doping-mediated lattice engineering of monolayer ReS2 for modulating in-plane anisotropy of optical and transport properties	In-person
P2	P2-I-33	Taesoo KIM	Sungkyunkwan University	High-mobility junction field-effect transistor via graphene/MoS2 heterointerface	In-person
P2	P2-I-34	You Kyoung Chung	Sungkyunkwan University	Evaluating the physical properties of 1D Ta2Ni3Se8 semiconducting materials as a prominent channel resource: structural, electronic, transport, and magnetic Properties	In-person
P2	P2-I-35	Giheon Kim	Sungkyunkwan University	Investigation of Electron and Hole Trap States in MoTe2 by Hysteresis Analysis and Current Deep Level Transient Spectroscopy	In-person
P2	P2-I-36	Chaeyeon Shin	Sungkyunkwan University	Ti3C2Tx MXene Based Neuromorphic Synaptic Device	In-person
P2	P2-I-37	Kim My Tran	Sungkyunkwan University	Electron-withdrawing Graphdiyne Thin Film Transistor and Its Application in Gas Sensor	In-person
P2	P2-V-01	Shivani Dhall	DAV College	Synthesis and Structural studies of CNT/Cu composites: future lightweight wires	Virtual
P2	P2-V-02	Yunxiang Bai	University of Chinese Academy of Sciences	Mechanical Behavior of Defect-Free Carbon Nanotubes	Virtual
P2	P2-V-03	Fenfa Yao	Zhejiang University	Confinement effect induced conformation change of one-dimensional phosphorus chains filled in carbon nanotubes	Virtual
P2	P2-V-04	Ana Cadena	Wigner Research Centre for Physics	Liquid phase encapsulation into carbon nanotubes: endohedral doping and 6-armchair graphene nanoribbon growth	Virtual
P2	P2-V-05	Alexander Chernov	Russian Quantum Center	Magnetic nanoribbons inside single-walled carbon nanotubes	Virtual
P2	P2-V-06	Toshihiko Fujimori	Sumitomo Electric Industries, Ltd.	Toward high-strength carbon nanotube fibers: In situ alignment technique via floating-catalyst chemical vapor deposition	Virtual
P2	P2-V-07	Shuhui Wang	The University of Tokyo	1D Heterostructures grown on Semi-conducting Single-walled Carbon Nanotube Thin Film	Virtual
P2	P2-V-08	Julio Chacon	Yachay Tech University	Understanding the Electron-Doping Mechanism in Potassium-Intercalated Single-Walled Carbon Nanotubes	Virtual
P2	P2-V-09	Zeyao Zhang	Peking University	Stable Doping of Single-Walled Carbon Nanotubes for Flexible Transparent Conductive Films	Virtual
P2	P2-V-10	Mohammad Alsubhani	The Catholic University of America	Electrical Piezoimpedance of Carbon Nanotube Yarns Towards Development of Multifunctional Sensors.	Virtual
P2	P2-V-11	Xuanzhang Li	Tsinghua University	Gate-tunable Contact-induced Fermi Level Shift in Semimetal	Virtual
P2	P2-V-12	Iriana Garcia Guerra	Catholic university of America	Piezoresistive response of carbon nanotube fibers under axial compression	Virtual
P2	P2-V-13	NAN FANG	RIKEN	Hexagonal boron nitride as an ideal substrate for carbon nanotube photonics	Virtual
P2	P2-V-14	Tannaz Tayyarian	The Catholic University of America	Integrated Temperature Sensing Using Carbon Nanotube Yarn Monofilament Composites: Initial Experimental Results	Virtual
P2	P2-V-15	Kotaro Ota	Hosei University	Control of the thermoelectric properties of single-walled carbon nanotubes films by Joule annealing and doping	Virtual
P2	P2-V-16	SWEETY VERMA	INJE UNIVERSITY	Optical properties and structure of BYZGO: Er3+ nanomaterials with green light emission for modern lighting applications	Virtual
P2	P2-V-18	SE JIN PARK	Sungkyunkwan University	Enhanced upconversion photoluminescence by quasi-periodic metalinsulator-metal (MIM) platform and photochemical switching application	Virtual
P2	P2-V-19	Je-Jun Lee	Sungkyunkwan University	Mechanism Verification of Persistent Photoconductivity Effect in ReS2 Thin Film Transistors	Virtual
P3	P3-I-01	Antonia Kagkoura	National Hellenic Research Foundation	Controlled chemical functionalization toward 3D-2D carbon nanohorn-MoS2 heterostructures with enhanced electrocatalytic activity for protons reduction	In-person
P3	P3-I-03	Ahmad Tayyebi	UNIST	Efficient Ammonia Electrosynthesis from Nitrate on Ru @ TiO2 Nanosheets	In-person
P3	P3-I-04	Tanja Kallio	Aalto University	Enhancing LiNi0.6Mn0.2Co0.2O2 based lithium battery electrode performance by incorporating carbon nanomaterials	In-person
P3	P3-I-05	Yun Seong Cho	Sungkyunkwan University	Solution-Processed Uniform Nanocatalyst Film with Binder-Free Graphene Layer for Electrochemical Water Splitting	In-person
P3	P3-I-06	Jun Beom Kim	KAIST	Three-Dimensional Interfacial Gelation of Reduced Graphene Oxide for Large Capacity Supercapacitor application	In-person
P3	P3-I-08	Ji Soo Roh	University of Manchester	Ultrathin rGO-MoS2 Hybrid Membrane for Vanadium Redox Flow Battery with Low Vanadium Crossover	In-person

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P3	P3-I-09	Keshab Pandey	Daegu University	Coffee Waste-Derived Porous Carbon Based Flexible Symmetric Supercapacitors	In-person
P3	P3-I-10	Ghanashyam Gyawali	Daegu University	Flower-like Molybdenum Disulfide for Efficient Hydrogen and Oxygen Evolution Reaction	In-person
P3	P3-I-11	Laud Adofo	Sungkyunkwan University	High hydrogen generation via interplay between organic molecules and transition metal dichalcogenide monolayers	In-person
P3	P3-I-12	Yo Seob Won	Sungkyunkwan University	Surface reconstruction in Fe-doped NiPS3 to boost oxygen evolution reactions	In-person
P3	P3-I-15	Hyejung Lee	Korea Electrotechnology Research Institute	High Performance Anode Materials for LIB by Hierarchical Graphene Structures	In-person
P3	P3-I-16	Camille PINCHART	CEA	Electrolyte under 1D CNT confinement: the route to operation of Lithium Metal Polymer Batteries at ambient temperature.	In-person
P3	P3-I-17	Hoon Ju Lee	Ulsan National Institute of Science and Technology	Stabilization of metastable phase WS2 quantum dots via Re doping for enhanced HER performance	In-person
P3	P3-I-18	Sang Ha Baek	Sungkyunkwan university	Carbon nanofiber as conductive substrate for zinc metal anode	In-person
P3	P3-I-19	Yang Liu	Sungkyunkwan University	Unraveling the Unique Function of Amorphous Support in Single-atoms Electrocatalyst for Enhanced Hydrogen Evolution	In-person
P3	P3-I-20	SARA AJMAL	Sungkyunkwan University	Size-dependent electrocatalytic stability and activity of RuX@CN Toward pH-Universal Hydrogen Generation via Water Reduction	In-person
P3	P3-I-21	QIAN WANG	Sungkyunkwan University	Fe, N-containing Porous Carbon Modified Separator for High Performance Lithium Sulfur Batteries	In-person
P3	P3-I-22	MENGFANG LIANG	Sungkyunkwan University	Stabilized non-noble metal Cu and Co Dual Single Atoms on Blue TiO2 for enhanced Photocatalytic Hydrogen Evolution	In-person
P3	P3-I-23	Michele Ghini	Italian Institute of Technology	Doped metal oxide nanocrystals and 2D materials hybrid systems for light-driven energy storage	In-person
P3	P3-I-24	Haifa taoum	École Polytechnique-CNRS, IP Paris	Functionalized Single-Wall Carbon Nanotubes as a potential application for gas leakage detection in Li-ion batteries	In-person
P3	P3-I-25	Sin Lee	Hanyang University	Transition metal dichalcogenide nanohybrid theragnostics for pathogen infection	In-person
P3	P3-I-26	Hyunji Lee	Hanyang university	Multivalent Peptide Phases on Two-dimensional Nanosheets for Bacterial Sensing and Therapy	In-person
P3	P3-I-27	Han Young Woo	Seoul National University	Fabrication of SERS active nanocomposites for in vivo application	In-person
P3	P3-I-28	Min Jeong Lee	seoul national university	Topical Protein Delivery using Single-walled Carbon Nanotubes	In-person
P3	P3-I-29	Wujoon Cha	Sungkyunkwan University	Charge transfer of Aβ-proteins examined by a graphene-enhanced Raman spectroscopic platform	In-person
P3	P3-I-30	Hongdan Wang	Sungkyunkwan University	Selectively Regulating the Chiral Morphology of Amino Acid Assisted Chiral Gold Nanoparticles with Circularly Polarized Light	In-person
P3	P3-I-32	Jinhwa Park	Sungkyunkwan University	Roll-to-roll printed thin-film transistor-based ion sensor for wirelessly monitoring cell's physiology	In-person
P3	P3-I-33	Jinho Lee	Korea advanced institute of science and technology	Investigation of Au Nanoparticles Functionalization on Various Metal Oxides toward Highly Sensitive and Selective Gas Sensor Array	In-person
P3	P3-I-34	Jin Hyun Park	Sungkyunkwan University	N-Triflyl phosphoric triamide as a powerful organic sensor for chemical warfare agent	In-person
P3	P3-I-35	Hao Yang	Sungkyunkwan university	Roll-to-roll imprinted and printed flexible plasmonic field-effect transistor for near infrared bio-image sensors	In-person
P3	P3-I-36	Han Truong	Sungkyunkwan University	Innovative COVID-19 analysis by rapid (light) enhanced RPA (iCARE)	In-person
P3	P3-I-37	SADA VENKATESWARLU	GACHON UNIVERSITY	Icosahedral Pd Nanoparticles Embedded BN Nanotubes: Outstanding and Ultra stable Hydrogen Evolution Reaction	In-person
P3	P3-I-38	Jongwoon Kim	Korea University	Improved ion selectivity of graphene oxide membranes in terms of the reduced interlayer spacing and vertically confined channels for energy harvesting application	In-person
P3	P3-V-02	Lingling Wang	Sungkyunkwan University	Oxygen-bridged Vanadium Single-atom Dimer Catalysts Promoting High Faradic Efficiency of Ammonia Electrosynthesis	Virtual
P3	P3-V-03	Yixuan Wang	Sungkyunkwan University	Acidification and bubble template derived porous g-C3N4 for efficient photodegradation and hydrogen evolution	Virtual
P3	P3-V-04	Hanxuan Wang	EPFL	Bioengineering a glucose oxidase nanosensor for near-infrared continuous glucose monitoring	Virtual
P3	P3-V-05	Estefânia Martins	CDTN	Development of a nanoplatform based on oxidized multi-walled carbon nanotubes, chitosan and P. brasiliensis peptides as a new therapeutic approach for paracoccidioidomycosis	Virtual
P3	P3-V-06	Dain Kim	Yonsei University	Graphene-based Sensor for High-resolution ECoG Detection	Virtual
P3	P3-V-07	Kaito Nakamae	Waseda university	High energy density Li-S battery with active materials and salts held by carbon nanotube paper	Virtual
P3	P3-V-08	Tomotaro Mae	Waseda University	Self-supporting negative electrode of silicon monoxide held by carbon nanotubes for stable and high-capacity secondary batteries	Virtual
P3	P3-V-09	Aejin Lee	Sungkyunkwan University	Diabetes Type Discrimination by Nanoparticles Based Sandwich Immunoassay	Virtual
P3	P3-V-10	Seok Cheol Kim	Sungkyunkwan University	DNA Sensing with Gold Nanoparticle and Toehold Mediated Strand Displacement	Virtual

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P3	P3-V-11	Jinyoung Park	Sungkyunkwan University	PEGylated nanocarrier albumin-bound steroidal ginsenoside derivatives improve severe infectious disease-mediated hyper-inflammatory responses	Virtual
P3	P3-V-12	Donghyuk Seo	Sungkyunkwan University	TGFBIp as Potential Theragnostic Target for Severe infecious diseases	Virtual
P3	P3-V-13	Gyu-Hee Kim	Sungkyunkwan University	Non-fullerene Organic Photovoltaics facilitated efficient photon harvesting under indoor lighting environments	Virtual
P3	P3-V-14	HyeonYeong	Sungkyunkwan University	Efficient morphological modification using two miscible Non-fullerene acceptors in low-intensity indoor irradiation condition	Virtual
P3	P3-V-15	Bowen Zhang	University of Tokyo	Poly(triarylamine) wrapped carbon nanotubes as efficient electrodes for Li-TFSI free high-stability perovskite solar cells	Virtual
P4	P4-I-01	Riya Sebait	Sungkyunkwan University	Defect-Induced Trion in Monolayer WS2 at Room Temperature	In-person
P4	P4-I-02	Hongguk Min	SungKyunKwan University	Nodal-line Superconductor in Hexagonal ABC Dirac Semimetals	In-person
P4	P4-I-03	Lan Anh Nguyen	Sungkyunkwan University	Spin-Selective Hole−Exciton Coupling in V-Doped WSe2 Ferromagnetic Semiconductor at Room Temperature	In-person
P4	P4-I-04	Yoonhee So	Hanyang University	Antioxidative WS2 nanosheet antipyrotics with anti-apoptotic and anti-inflammatory activities for Treatment of Deep Burns	In-person
P4	P4-I-05	Pai Li	Institute for Basic Science	Origin of the unexpected stability of metastable T phase MoS2	In-person
P4	P4-I-06	Xu Wei	Sungkyunkwan University	Synthesis and characterization of Metal-rich Layered chalcogenides TaM2Te2 (M=Co, Ni): Structural Variant with Peierls Distotion	In-person
P4	P4-I-08	Peng PENG	IBS CMCM	Thickness control of molybdenum disulfide grown on sapphire	In-person
P4	P4-I-09	Isabella Gasparutti	Sungkyunkwan University, CINAP	How Clean Is Clean? Recipes for van der Waals Heterostructure Cleanliness Assessment	In-person
P4	P4-I-10	Soo Ho Choi	Sungkyunkwan University	Epitaxial Single-Crystal Growth of Transition Metal Dichalcogenide Monolayers via Atomic Sawtooth Au Surface	In-person
P4	P4-I-12	Tuan Dung Nguyen	CINAP	Modulating magnetism via Se-vacancy states in WSe2	In-person
P4	P4-I-13	Hyungsik Oh	Sejong University	Achieving Fermi-Level Pinning Free contact using Mo2C electrode	In-person
P4	P4-I-14	Hyeongjoon Kim	Ulsan National Institute of Science and Technology	Chemical Vapor Deposition Growth of Amorphous Boron Nitride	In-person
P4	P4-I-15	ANDREW BEN-SMITH	Sungkyunkwan Univeristy	Hygroscopic Na residue-mediated photocatalytic degradation of transition metal dichalcogenide monolayers under moisture-rich condition.	In-person
P4	P4-I-16	Sehwan Park	Sungkyunkwan University	Tailoring Domain Morphology in Monolayer NbSe2 and WxNb1−xSe2 Heterostructure	In-person
P4	P4-I-17	Minsung Kang	Korea Institute of Science and Technology	Dispersant-removable purification method for boron nitride nanotubes through Lewis acid-base interaction	In-person
P4	P4-I-18	Hyuntae Hwang	Ulsan National Institute of Science and Technology	Hexagonal boron nitride for anti- and de-icing heating system with Radio-frequency-transmitting and thermal spreading properties	In-person
P4	P4-I-19	Jiwon Kim	Sungkyunkwan University	Synthesis of high-quality violet phosphorus crystals	In-person
P4	P4-I-20	Jina Lee	Sungkyunkwan university	Room-temperature direct growth of wafer-scale transition metal dichalcogenide films via remote plasma-assisted chemical vapor deposition	In-person
P4	P4-I-21	Joseph Baidoo	Sungkyunkwan University	Sequential growth of vertical transition metal dichalcogenide heterostructures on rollable aluminum foil	In-person
P4	P4-I-22	Minsu Kim	UNIST	Low-Dielectric Constant of Amorphous Boron Nitride Film	In-person
P4	P4-I-23	Huong Nguyen	Sungkyunkwan University	Enhanced catalytic activity of spatial distribution of active sites in heterogeneous 1T′/2H phases	In-person
P4	P4-I-24	Mai Nagano	Tokyo Metropolitan University	Synthesis of Hetero Transition Metal Dichalcogenide Nanotubes	In-person
P4	P4-I-25	Byeong Wook Cho	Sungkyunkwan University	Escalating ferromagnetic order via Se-vacancy near vanadium in WSe2 monolayers	In-person
P4	P4-I-26	Dohyun Kim	Sungkyunkwan university	Atomic scale thermopower imaging in 1T-TaS2	In-person
P4	P4-I-27	Mallesh Baithi	Sungkyunkwan University	Incommensurate antiferromagnetic order in 2D insulator CrPSe3	In-person
P4	P4-I-28	Houcine Bouzid	Sungkyunkwan University	Tunable magnetic properties of van der Waals SnS2 semiconductor via transition metal dopants	In-person
P4	P4-I-29	Taewoo Ha	Sungkyunkwan university	Detecting orbital Hall effect in Weyl semimetal WTe2 via terahertz polarization imaging	In-person
P4	P4-I-30	Jeong Won Jin	Sungkyunkwan university	Investigation of epitaxial WS2 monolayer on zigzag Au substrate using scanning tunneling microscopy	In-person
P4	P4-I-31	TRANG TRAN	Sungkyunkwan University	Enhanced Radiative Decay and Quantum Yield of Monolayer WS2 on the hBN Substrate	In-person
P4	P4-I-32	Gyounghoon Oh	Sungkyunkwan University	Electrical properties of Two-Dimensional Tellurene as PMOS	In-person
P4	P4-I-33	Duc Vu	Sungkyunkwan University	Graphene encapsulated in high k-dielectric as charge trapping layer for MoS2-based memory devices	In-person

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P4	P4-I-34	Byung-wook Ahn	Sungkyunkwan university	Passivation of Sulfur Vacancies and Its Electrical Properties on Monolayer Molybdenum Disulfide	In-person
P4	P4-I-35	Bumsub Song	Sungkyunkwan University	Reversible switching of bistable defect charge states in monolayer MoS2	In-person
P4	P4-I-36	Yeonju Lee	Ulsan National Institute of Science and Technology	2D confined space of graphene sandwich for solid-state organic reaction	In-person
P4	P4-I-37	Blazej Podlesny	Silesian University Of Technology	Modulation of the aqueous two phase extraction method to increase the resolution of SWCNT separation	In-person
P4	P4-V-01	Yongjia Zheng	The University of Tokyo	Experimental realization of the WS2-based 1D vdW heterostructure	Virtual
P4	P4-V-04	Wanyu Dai	The University of Tokyo	Experimental realization of NbS2 based 1D van der Waals heterostructures	Virtual
P4	P4-V-05	Yoonsok Kim	Hanyang University	High-Performance MoS2/p+-Si Heterojunction Field-Effect Transistors by Interface Modulation	Virtual
P4	P4-V-06	Ruixi Zhang	The University of Tokyo	Synthesis and structural characterization of Boron Nitride Nanotubes with the Chirality-Sorted Carbon Nanotubes as the Template	Virtual
P4	P4-V-07	MD ASHIQUR RAHMAN	Doctoral Student	Synthesis of relatively small-diameter WS2 nanotubes by sulfurization of poly(ethylene glycol) treated thin tungsten oxide nanowires	Virtual
P4	P4-V-08	Luhing Hu	Yonsei University	Flexible active-matrix micro-LED display via monolithic integration of MoS2 backplane circuitry	Virtual
P4	P4-V-09	Anh Tuan Hoang	Yonsei University	Flexible electronics on ultrathin glass using low-temperature grown MoS2	Virtual
P4	P4-V-10	Beom Jin Kim	Yonsei University	Flexible X-ray/Vis Detector Enabled by 2D Materials Backplane	Virtual
P4	P4-V-11	Stefan Wolff	Friedrich-Alexander-Universität Erlangen-Nürnberg	Twisted bilayer antimonene	Virtual
P4	P4-V-12	LIU YIJUN	Okayama University	Room temperature synthesis of Janus MoSeS by optimal plasma treatment conditions	Virtual
P5	P5-I-02	Thomas Liu	Université Paris-Saclay	Optical investigation of C96 graphene quantum dots	In-person
P5	P5-I-03	Dmitry Levshov	University of Antwerp	Inner-to-outer wall energy transfer in double-wall carbon nanotubes revealed by detailed optical spectroscopy	In-person
P5	P5-I-04	Nicolas Zorn	Heidelberg University	Probing Carrier Dynamics in sp3-Functionalized Single-Walled Carbon Nanotubes with Time-Resolved Terahertz Spectroscopy	In-person
P5	P5-I-05	Finn Sebastian	Heidelberg University	Absolute quantification of sp3 defects in carbon nanotubes by Raman spectroscopy	In-person
P5	P5-I-06	Dawid Janas	Silesian University of Technology	High-precision separation of carbon nanotubes by the aqueous two-phase extraction method	In-person
P5	P5-I-07	Anatoli SERGHEI	University of Lyon	Broadband Dielectric Spectroscopy on Polymer Nanotubes, Nanowires, Attograms and Zeptograms of Matter	In-person
P5	P5-I-08	Sonja Wieland	Heidelberg University	Influence of the Dielectric Environment on Trion Emission in Electrostatically Doped Networks of (6,5) Carbon Nanotubes	In-person
P5	P5-I-10	)ido Denier van der Go	University of Vienna	Fluorescence and Optical Absorption Spectroscopy on substitutionally and endohedrally functionalized SWCNTs	In-person
P5	P5-I-11	Joselyn Benalcazar	University of Vienna	Towards understanding fluorescence microscopy on single chirality single-walled carbon nanotubes	In-person
P5	P5-I-12	Roland Gillen	Friedrich-Alexander-Universität Erlangen-Nürnberg	Family behavior and Dirac bands in armchair nanoribbons with 4-8 defect lines	In-person
P5	P5-I-13	Christine Elias	ENS Paris Saclay	OPTICAL SPECTROSCOPY OF NONPLANAR GRAPHENE NANORIBBONS WITH FJORD EDGES	In-person
P5	P5-I-14	Kyung-Hun Ko	Sungkyunkwan University	Observation of orbital Hall effect by orbital torque	In-person
P5	P5-I-15	Hiroyuki Nishidome	Tokyo Metropolitan University	Influence of Laser-intensity on the Fermi-level dependence of high-harmonic generation from single-walled carbon nanotubes	In-person
P5	P5-I-16	Sumin Kim	Spin information Laboratory	Measurement of spin-orbit torque in Ti/CoFeB bilayer	In-person
P5	P5-I-18	Ravindra Pandey	Michigan Technological University	2D Ultrathin Tungsten Nitride: Theoretical study of electronic and mechanical properties	In-person
P5	P5-I-19	Jaemo Jeong	SungKyunKwan University	First-principles Study on Topological Phase Transition in NaZnBixSb1−x	In-person
P5	P5-I-21	Peizhe Tang	Beihang Univeristy	Correlated states realized in 1D Morié structure in double-Wall Carbon Nanotube with torsions	In-person
P5	P5-I-23	Chao Zhao	Ulsan National Institute of Science and Technology	Temperature dependent graphene wrinkle formation: a theoretical study	In-person
P5	P5-I-24	Churlhi Lyi	SUNGKYUNKWAN UNIVERSITY	First-principles calculations of topological nodal line semimetals and coexisting higher-order insulating states in γ-GeSe under strains.	In-person
P5	P5-I-25	sunam Jeon	Sunkyunkwan university	First-principles calculations of weak-type Stiefel-Whitney insulators in two dimensions	In-person
P5	P5-I-26	Cheng Qian	Ulsan National Institute of Science and Technology	A comprehensive assessment of empirical potentials for carbon materials	In-person
P5	P5-I-29	Pavel Sorokin	National University of Science and Technology MISiS	Theoretical investigation of chirality transitions in carbon nanotubes exposed at a high temperature and slow elongation	In-person

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P5	P5-I-30	Junho Lee	Sungkyunkwan university	A survey of deep learning-based generative model for revealing 2D magnesium hydride crystal structure	In-person
P5	P5-I-31	Seon Bin Song	Sungkyunkwan university	DFT study for patterning of twisted bilayer graphene	In-person
P5	P5-I-32	Sang-Hyeok Yang	Sungkyunkwan University	Deep learning-assisted quantification of atomic defects in 2D materials	In-person
P5	P5-I-33	Minsun Park	Sungkyunkwan University	Thiolated Amino Acids Based Synthesis of Tip-Modified Au Double Rings for SERS Measurement	In-person
P5	P5-V-01	Sol Lee	Yonsei University	In-situ TEM Observation of Semi-templated Synthesis of Higher Fullerenes	Virtual
P5	P5-V-02	Umedjon Khalilov	University of Antwerp	Pre-nucleation mechanisms of organic carbon nanocrystals	Virtual
P5	P5-V-03	Umedjon Khalilov	University of Antwerp	Feedstock effect in the catalyzed synthesis of encapsulated nanocarbons	Virtual
P5	P5-V-04	Kazunori Fujisawa	Shinshu University	Raman-based Quantitative Point Defect Density Comparison in Graphenic System	Virtual
P5	P5-V-05	Lei Shi	Sun Yat-sen University	Raman spectroscopic studies on confined-synthesized graphene nanoribbons	Virtual
P5	P5-V-06	Achim Hartschuh	LMU Munich	Probing the Ultrafast Dynamics of Excitons in Single Semiconducting Carbon Nanotubes	Virtual
P5	P5-V-07	YA FENG	The University of Tokyo	Radial breathing mode of individual carbon nanotubes shows no temperature dependence	Virtual
P5	P5-V-08	Yuguang Chen	Peking University	Accurate height measurement of carbon nanotubes using scanning probe microscopy	Virtual
P5	P5-V-09	Bo Wang	Zhejiang University	In-situ observation of contact transform in metal carbide-carbon nanotube junction	Virtual
P5	P5-V-10	Bryant Jerome	Rice University	Outcoupling Hyperbolic Modes from Aligned Carbon Nanotube Films	Virtual
P5	P5-V-11	Yoshiyuki Miyamoto	National Instituute of Advanced Indusrtial Science and Technology (AIST)	Laser-assisted selection of orientations and diameters of carbon nanotubes studied by ab initio simulations	Virtual
P5	P5-V-12	Florian Fuchs	Fraunhofer Institute for Electronic Nano Systems	Simulation of the impact of intercalation and flake properties in graphene-based macromaterials	Virtual
P5	P5-V-13	Daniel Stormer Vadseth	University of Newcastle, Australia	One-Dimensional van der Waals Heterostructures: A Computational Benchmarking Study	Virtual
P5	P5-V-14	Takazumi Kawai	Tokyo City University	Diffusion of Oxygen Atom Across Graphene Oxide Sheet Through Atomic Vacancy: DFT Calculations	Virtual
P5	P5-V-15	Hyundong Kim	Sungkyunkwan University	Theoretical Approach to Investigate Photocatalytic Activity of TiO2 Nanoparticles	Virtual
P5	P5-V-16	HyoungChul Ham	Sungkyunkwan University	Theoretical study for therapeutic effect of photosensitizers through the excited state dynamics and band analysis	Virtual
P5	P5-V-17	Chang-Youn Moon	Korea Research Institute of Standards and Science	Analogous atomic and electronic properties between VN and VNCB defects in hexagonal boron nitride by first-principles	Virtual
P5	P5-V-18	Lukas Krisna	Osaka University	Moiré phonons in graphene/hexagonal boron nitride moiré superlattice	Virtual
P5	P5-V-19	Riichiro Saito	Tohoku University	Origin of Complex Raman tensor in Black Phosphorus and 2D materials	Virtual
P5	P5-V-20	Jacques Doumani	Rice University	Chiroptical effect in aligned carbon nanotube films	Virtual
P6	P6-I-01	Xiaogang Sun	Manyuan Cai	Far-infrared radiation papers and applications	In-person
P6	P6-I-02	Juan Vilatela	IMDEA Materials	Progress in CNT fibre development for structural applications	In-person
P6	P6-I-03	s GOISLARD DE MONS	NAWATECHNOLOGIES	Roll-to-roll manufacturing of Vertically Aligned Carbon Nanotube electrodes for supercacitors	In-person
P6	P6-I-06	Yunho Jeong	Pusan National University	Engineering the wet spinning of carbon nanotube fibers in surfactant/water system	In-person
P6	P6-I-07	Philip McKeown	University of Cambridge	High performance CNT fibers with ultra-high linear density	In-person
P6	P6-I-08	KIM SEONGRYEONG	Institute of Quantum Biophysics	Roll-to-roll printed Mini well for Efficient Detection of Infectious diseases with Convenient (MEDIC) RT-qPCR device	In-person
P6	P6-I-09	Seo Gyun Kim	Korea Institute of Science and Technology (KIST)	Process controlling for optimum molecular orientation and morphology of strong and multifunctional carbon nanotube fibers	In-person
P6	P6-I-10	Dongju Lee	Korea Institute of Science and Technology	Ultrahigh-performance carbon nanotube fibers by post-treatment	In-person
P6	P6-I-11	Shi Hyeong Kim	Korea Institute of Industrial Technology	High-generating electrical power from carbon nanotube yarn in ocean	In-person
P6	P6-I-12	Paola Ayala	University of Vienna	Key to high sensitivity of gases with a very effective desorption using single-walled carbon nanotubes	In-person
P6	P6-I-13	Sooyeon Jeong	Korea Electrotechnology Research Institute	Highly conductive chemically exfoliated graphene for solution-processable application	In-person
P6	P6-I-14	Kim Byeong Guk	Korea Electrotechnology Research Institute	Heteroatom doping of chemically exfoliated graphene by intense pulsed light	In-person

Poster Session

P6	P6-I-15	Seoho Jung	ETH Zurich	High-speed pick-and-place assembly of ultraclean carbon nanotubes	In-person
P6	P6-I-16	Sajjan Parajuli	Sungkyunkwan University	Green Foundry with Low Carbon Footprint for Sustainable Fabrication of Flexible Electronics	In-person
P6	P6-I-17	Miyeon Jeong	Sungkyunkwan University	Al2O3 supported Fe-oxide nanoparticles for the enhanced H2S decomposition activity under realistic conditions: in-situ DRIFTS and XPS studies	In-person
P6	P6-I-18	Huicheol Choe	Sungkyunkwan University	K doped TiO2 lattice for the enhanced photocatalytic activity of towards acetaldehyde and NO oxidation	In-person
P6	P6-I-19	Yosep Hwang	Sungkyunkwan University	Efficient indoor light-driven toluene decomposition via optimized band structure of Fe decorated metal oxides composite.	In-person
P6	P6-I-20	Sagar Shrestha	Sungkyunkwan University	A 13.56 MHz rectifier based on fully roll to roll printed IGZO diodes for mass productivity	In-person
P6	P6-I-21	Igor Bondarev	North Carolina Central University	Exciton-plasmon interactions in ultrathin periodically aligned single-wall carbon nanotube films	In-person
P6	P6-I-22	SeGi Yu	Hankuk University of Foreign Studies	Reduced Graphene Oxide in Polymer-Based Dielectric Composites	In-person
P6	P6-I-23	Hee Min Yang	Korea university	A nacre-inspired graphene oxide hierarchical composite with enhanced mechanical properties	In-person
P6	P6-I-24	Ioanna Sideri	National Hellenic Research Foundation	Engineered graphene featuring covalently incorporated amphoteric imidazole rings and electrostatically immobilised polyacrylic acid chains for selective electrochemical hydrogen peroxide production	In-person
P6	P6-I-27	Andrzej Dzienia	Silesian University of Technology	Isolation of monochiral single-walled carbon nanotubes with conjugated polymers: towards selective and efficient separation	In-person
P6	P6-I-28	Taehun Kim	Sungkyunkwan University	Skin softening thermal interface materials with carbon nanotubes achieving high thermal conductivity and low thermal contact resistance	In-person
P6	P6-I-29	FASEELA K.P.	Sungkyunkwan University	The Diels-Alder reaction and filler-polymer bifunctionalization strategy for strong healable conductive nanocomposites	In-person
P6	P6-I-31	Shin Jonghyun	Seoul national university	Effect of surface charge on the stability of Pickering emulsion using cellulose nanocrystals as a surface active particle	In-person
P6	P6-I-32	Sukki Lee	Korea Advanced Institute of Science and Technology	Aggregation-induced Emission of Matrix-free Graphene Quantum Dots via Selective Edge Functionalization	In-person
P6	P6-I-33	Yelim Kwon	Sungkyunkwan University	Synthesis of Hierarchical Micro/Mesoporous Carbon Materials and Its Applications	In-person
P6	P6-I-34	XIAODONG SHAO	Sungkyunkwan University	Covalent organic polymer assisted synthesis of super-uniform and high-density transition metal nanoclusters	In-person
P6	P6-I-36	Wei Zhang	Sungkyunkwan University	A fully roll-to-roll (R2R) printed olfactory receptor-mimicking carbonnanotube (CNT)-based disposable ammonia sensor label for monitoring food freshness	In-person
P6	P6-I-37	Min Sung Choi	SungKyunKwan University	Hierarchically porous carbon developed by lignin extracted from wooden biomass for high-performance electrode material of EDLC	In-person
P6	P6-V-01	Kazufumi Kobashi	National Institute of Advanced Industrial Science and Technology	N2 gas adsorption sites of single-walled carbon nanotube bundles: Identifying interstitial channels at very low relative pressure	Virtual
P6	P6-V-02	Sunwoo Kim	Ewha Womans University	Effect of Eluant Flow Speed Control in Gel Chromatography for Obtaining High-purity Metallic Single-walled Carbon Nanotubes	Virtual
P6	P6-V-03	Javier Ramirez Benavides	Skolkovo Institute of Science and Technology	Regeneration of single-walled carbon nanotube membranes for optical applications in the extreme ultraviolet range	Virtual
P6	P6-V-04	Frank Trixler	Ludwig-Maximilians-Universität München	Organic solid-solid wetting: a green chemistry approach to surface engineering of low-dimensional materials	Virtual
P6	P6-V-05	Mayra Peralta	Yachay Tech University	Electron and spin-phonon interaction in electron transfer in DNA	Virtual
P6	P6-V-06	Laura Meingast	Friedrich-Alexander-Universität Erlangen-Nürnberg	Raman characterization of single-walled carbon nanotubes functionalized with disulfide macrocycles	Virtual
P6	P6-V-07	Suyan Li	Osaka University	Spiked-shell microparticles of aerographite as ultralight fillers for flexible composites	Virtual
P6	P6-V-08	Kan Ueji	Tokyo Metropolitan University	Thermal Conductivity of Single-walled Carbon Nanotube Films in Vertical Electrolyte-gated Transistors	Virtual
P6	P6-V-09	Dewu Lin	National Institute of Advanced Industrial Science and Technology (AIST)	A novel approach to free "dead space" and modify interfacial features of carbon nanotube assemblies by a microwave shock	Virtual
P6	P6-V-10	Said Pashayev	Univ. Montpellier & CNRS	Experimental methods for nanofluidics: focus on sealing technology for delicate nanomaterials	Virtual
P6	P6-V-11	Renjini G R	NoPo Nanotechnologies India Private Limited	HiPCO® SWCNT membranes for effective conversion of seawater to potable water	Virtual
P6	P6-V-12	Takaki Yoda	Hosei University	Synthesis and properties of fluorescent carbon quantum dots using cellulose	Virtual

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We can promise that A-Tech System will solidify as a major company providing mass-production equipment by concentrating our resources and efforts on product quality enhancement.

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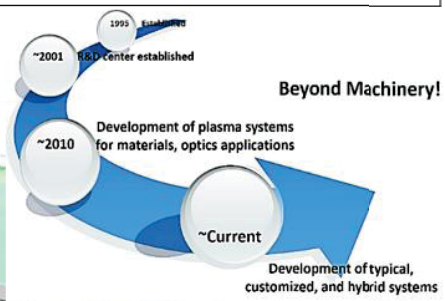
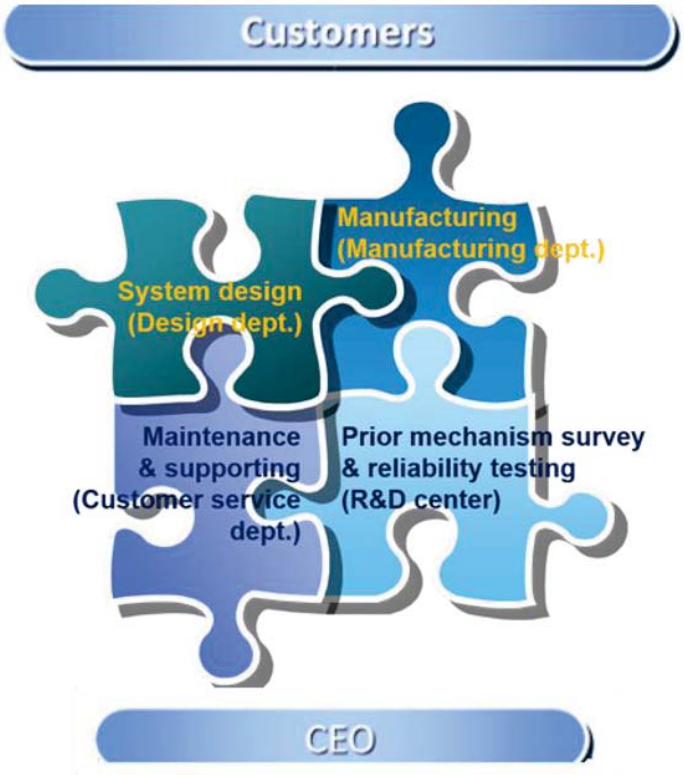
● COMPANY OVERVIEW

Company name	A-Tech Ssytem Co.
Established	Feb. 1995
Location	18, Annam-ro, 369 beon-gil, Bupyeong-gu, Incheon, 21312, Rep. of Korea
CEO(President)	Mr. Cho, Young Sang
Employees	20 ppl (2021)
Business fields	Machinery, Materials, Surface treatment, Energy harvesting, Semiconductor & Displays and other thin-film area
Main products	PVDs, CVDs, Etcher, Surface treatment system, Plasma reactors and Nanocarbon materials
R&D partnership	KITECH, KIST, K-CARBON, KIMS, KICT, SNU, SKKU, HYU, KAIST, and ETC.
Major customers	SAMSUNG, LG, SK HYNIX, National laboratories, Universities, and ETC.



Process Equipment Pioneer

● ORGANIZATION



● PATENTS & CERTIFICATES

● MAIN PRODUCTS

CVD : Chemical Vapor Deposition

PECVD	PECVD (Cluster, Batch) ICPCVD (Cluster, Batch) TCPCVD (Cluster, Batch)
Thermal CVD	Low pressure CVD Furnace (Batch)

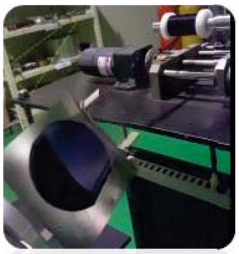
RIE : Reactive Ion Etcher

Dry etcher	CCP RIE, ICP RIE, TCP RIE (Cluster, Batch)

Customized manufacturing
: Hybrid systems(PVD-CVD combined system)

PVD : Physical Vapor Deposition

Sputter	Magnetron sputter (Cluster, Inline, Batch) Ion beam sputter (Batch) Sputter & E-beam evaporator (Roll to Roll)
Vacuum Evaporator	E-beam evaporator (Inline) Thermal evaporator (Roll to Roll) E-beam & thermal evaporator (Batch)
Cathodic Arc Deposition (AIP, Arc Ion Plating)	Non-filtered (Inline, Batch) Filtered (Batch)
Arc Discharge	CNT synthesis (Batch)



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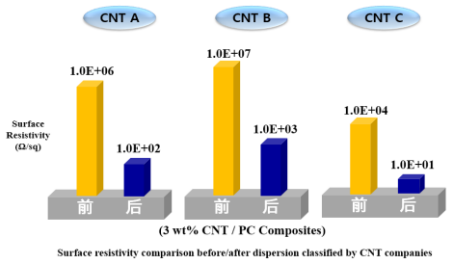
■ CNT Solution Co., Ltd. produces a CNT polymer MB (masterbatch) that improves the working environment and reduces logistics costs.

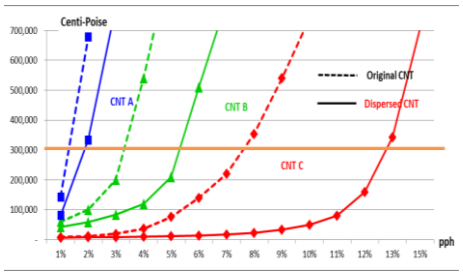
■ CNT Solution Co., Ltd. produces materials for household appliances, automobile ABS, PCABS, and permanent anti-static film/carrier/sheet with various colors with strong chemical resistance.

■ CNT Solution Co., Ltd. plays a key role in the energy and environment by developing hydrogen fuel cell separation plate and water electrolysis electrode plate with CNT performance UPGRADE.

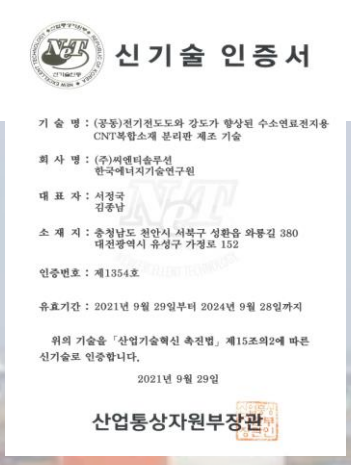
▶ **CNT** Dispersion effect



- 100 to 10,000 times more conductivity
- uniform quality
- Use a smaller amount than before



- Can be concentrated more CNT
- Highly concentrated CNT MB
- Highly conductive plastic composite materials



- **CNT Dispersion**
- **functional composite materials**
- **Innnovation company in chungnam**
- **Own technology patents**
- **Advanced technology product certification**
- **specializing in parts and materials**
- **Leading Industrial Convergence Companies and Products**
- **Quality management system certification company**

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shin@unist.ac.kr
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- Fundamental characterization of BN structures
- Their applications in (opto)electronic, energy storage and conversion devices.
- Synthesis and characterization of other 2D materials

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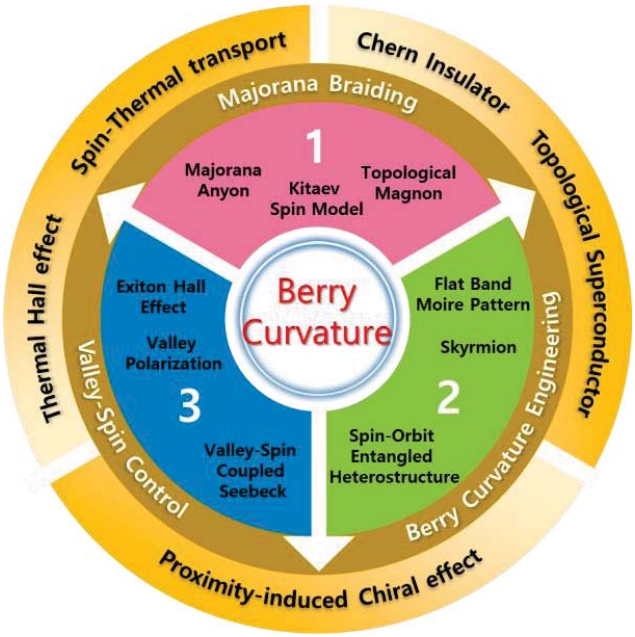
Center for Berry Curvature-based New Phenomena [SRC]

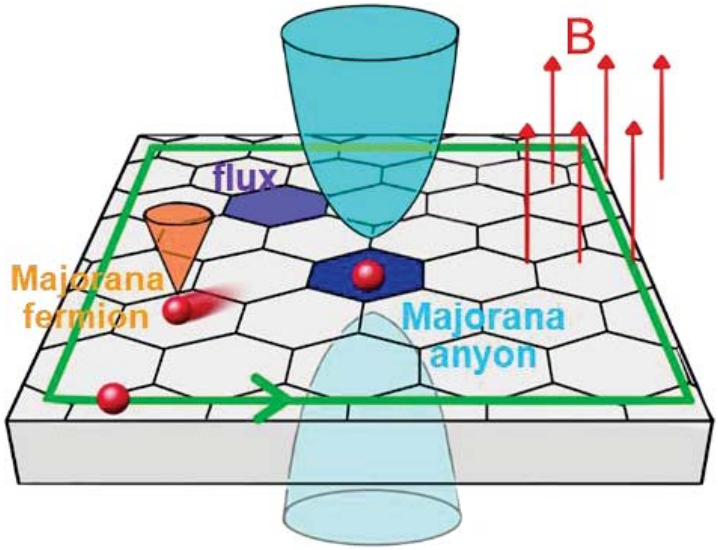
BeCaP
Center for Berry Curvature based New Phenomena

Director: Maeng-Je SEONG (Chung-Ang Univ.)

Homepage: https://becap-src.cau.ac.kr/

BeCaP was founded in 2020 as a Science Research Center (SRC) supported by Korean Government. BeCaP aims to expand the fermion-based Berry curvature research to boson and anyon systems emerging in condensed matter physics. The research topics of BeCaP include Kitaev honeycomb, Majorana braiding, topological superconductivity, Berry curvature engineering, spin-orbit phenomena, and valley-spin control.





1 Majorana Braiding

Kwang-Yong Choi (SKKU)
Kitaev honeycomb
Anyon braiding

Jae-Ho Chung (KU)
Topological magnon
Neutron scattering

Joonho Jang (SNU)
Topological Super-conductivity, Anyon

Sangjun Jeon (CAU)
Majorana zero mode
Anyon braiding, STM

2 Berry Curvature Engineering

Sug-Bong Choe (SNU)
Spin-orbit Entangled Heterostructure

Jeil Jung (UOS)
Flat band Engineering
Moiré physics

Seo Hyoung Chang (CAU)
Topological Hall effect
Skyrmion, X-ray

Jun Woo Choi (KIST)
Magnetic Skyrmion
Chiral Spin

3 Valley-Spin Control

Maeng-Je Seong (CAU)
Valley Polarization
Exciton Hall effect

Sang Kwon Lee (CAU)
Valley-Spin system
Thermal-Hall effect

Hyejin Ryu (KIST)
Valleytronics
Heterostructure, MBE

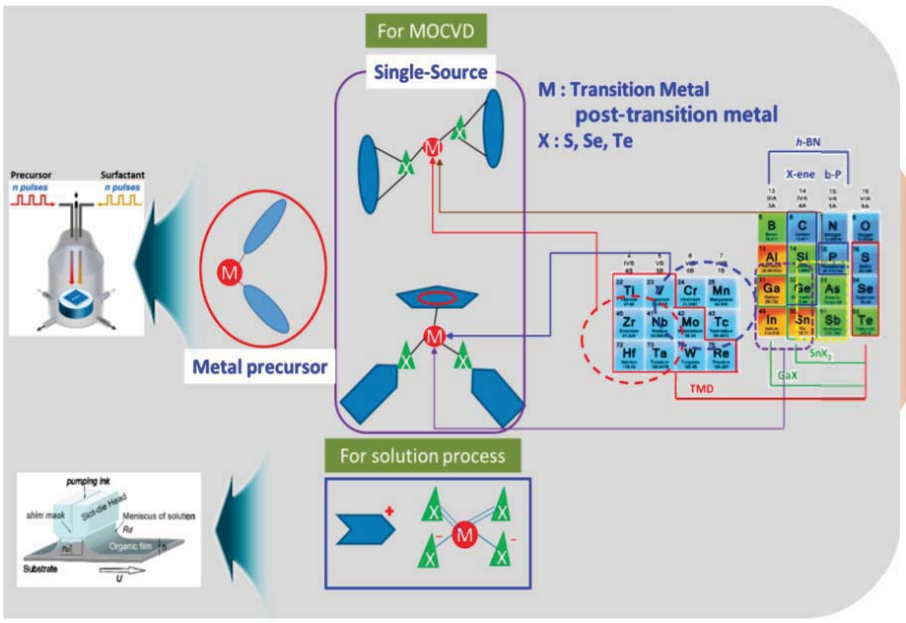
Young-Gui Yoon (CAU)
First-principles calculation

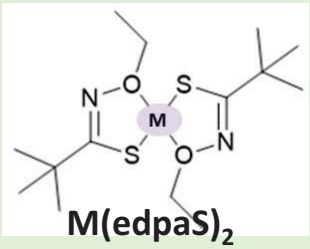
Ministry of Science and ICT | NRF National Research Foundation of Korea | Creative Materials Discovery Program | LMPRC Layered Materials Precursor Research Center

Layered Materials Precursor Research Center

PI :Jongsun Lim (KRICT)

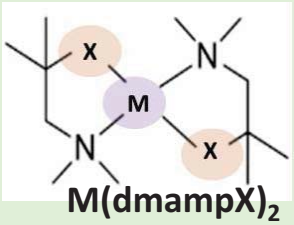
Precursor platform for van der Waals materials





$M(edpaS)_2$

M=Pd, Pt, In, etc



$M(dmampX)_2$

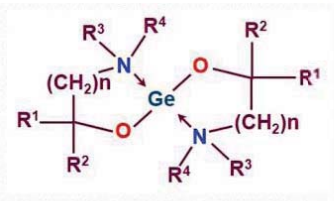
M=Pd, Pt, Sn, Mo, W, etc

X=S, Se

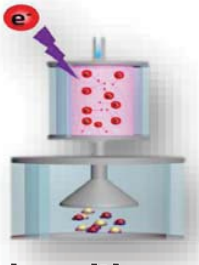
❖ Development of precursor platform for van der Waals materials

❖ Synthesis of precursors containing transition metals and chalcogen elements

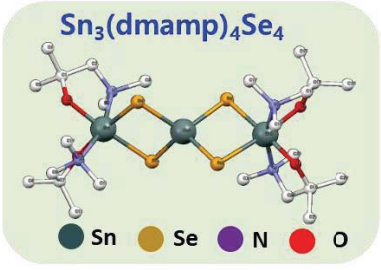
2 Synthesis and optoelectronic applications of van der Waals materials



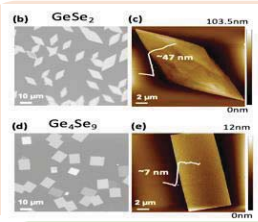
$Ge(dmamp)_2$



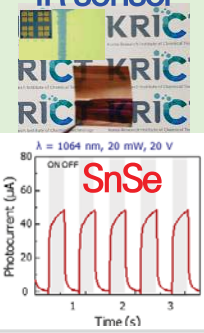
Vapor deposition process



Solution process



$GeSe_2$, Ge_4Se_9 growth using Ge precursors by MOCVD method



- ✓ Responsibility R=366 A/W, EQE=85,500% (@532nm)
- ✓ Responsibility R=124 A/W, EQE=14,500% (@1,064nm)
- ✓ Responsibility R=5 A/W, EQE=1,170% (@1,550nm)

KRICT Korea Research Institute of Chemical Technology | GIST Gwangju Institute of Science and Technology | POSTECH Pohang University of Science and Technology | 고려대학교 Korea University | KAIST | PAL 포항가속기연구소 Pohang Accelerator Laboratory | UNIST | KRISS 한국표준과학연구원 Korea Research Institute of Standards and Science

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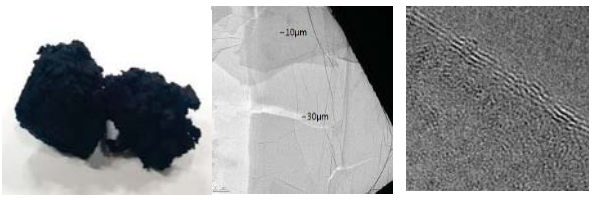
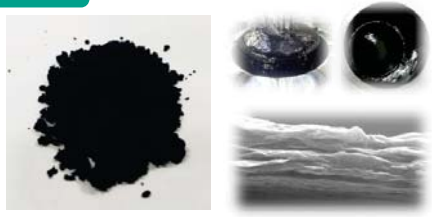
Graphene Oxide

- Paste type including water
- 3 ~ 5 layer
- Three types of rGO according to average lateral size.
  - CRO(05), CRO(25), CRO(50)



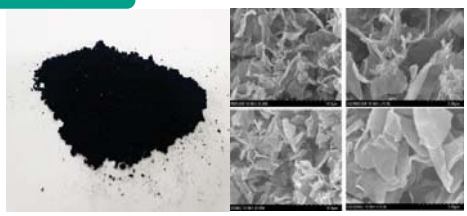
Reduced Graphene Oxide

- Paste including water or alcohol
- 3 ~ 5 layer
- Three types of rGO according to average lateral size.
  - CRG(05), CRG(25), CRG(50)
- Liquid Dispersion type
  - Ethanol, Isopropyl alcohol, etc.



Graphene (rGO) Powder

- Powder
- Layered controlled graphene.
- Two types depending on the number of layers.
  - 3 ~ 5 layers, 6 ~ 10 layers



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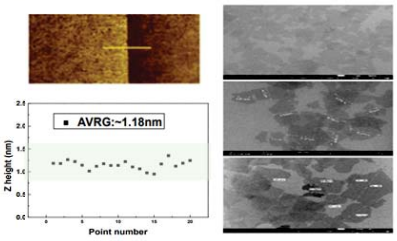
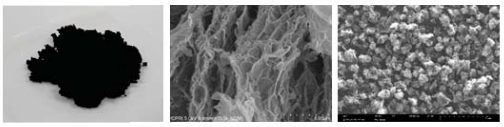
- Graphene Composition Having Liquid Crystalline property ; Production of Single-layer, High-quality graphene oxide
- Acid Free ; Synthesis of graphene oxide by high-temperature heat treatment of inorganic salts without sulfuric acid



- Thermal Reduction Graphene Oxide ; Excellent conductor of heat and electricity with high surface area

Specifications	Unit of Measure	Value
Contents, Impurities	%	Carbon : 97~98, Impurities : 0.1 〈
Surface area	m^2/g	800~900
Conductivity	S/cm	185 at 1.00g/cc



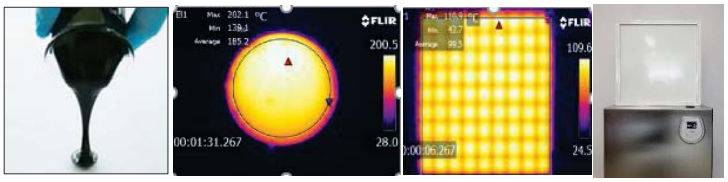
Contractors

KAIST | SAMHWAN TF (SAMHWAN Tandem Fashion) | LG Energy Solution | KRICT | cardoc | SONO INDUSTRIES | SENKO | 가드넥 (주) GUARDNEC Co.,Ltd | DAEJOO

TERAON Co., Ltd.
www.teraon.co.kr
031-709-2020

Heating materials based on nano carbon

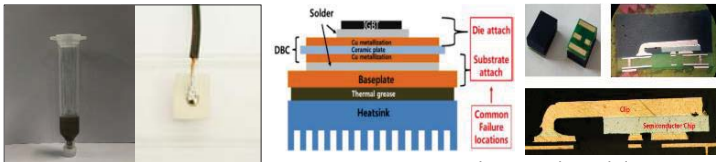
- Rapid heat-up rate over 250℃
- High temperature durability, flexibility
- For electric vehicles, home appliances, architecture, etc.
- Suppling radiation heating film heater for EV
- Owns more than 100 recipes and database



Die attach paste

Bondable material like a pure silver

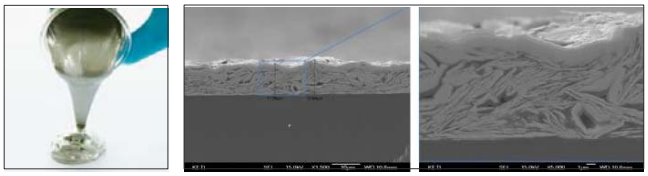
- Low temp. sintering and soldering without separate flex
- High power LED package, High power RF chip Suitable for power semiconductor, APU, SiC
- pressure-free bonding material (SiC, GaN)
- High thermal conductivity up to 340 W/mK



[SiC IGBT package and module]

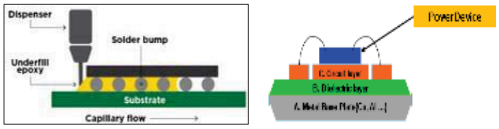
Flexible conducting material with high thermal resistance

- Heat resistance over 200℃
- Ag migration prevention
- Excellent conductivity & flexibility
- Excellent price competitiveness
- Conductive paste for automotive seat warmer



Insulating materials with high thermal resistance & high dielectric strength

- T_g less / Fine pitch underfill material
- Low CTE / Excellent flow
- More than 5kV (@100㎛)
- Power semiconductor package application test



HNS
Human, Nature & Society

Contact | ☎031-765-6714
http://www.hnss.co.kr

HNS is a leading world-best manufacturer of **TIM**(Thermal Interface Material) and a frontier of **Si/rGO** composite mass production technology of anode material.

Products

≫TIM(Thermal Interface Material)

- Full range products available (TIM, Heat Pipe, Vapor Chamber)
- Binder Design and Variety
- Excellent Oil Bleeding Control
- Low impurity

Si/rGO Technology

* rGO: Reduced Graphene Oxide

- Water-dispersed
- Low-SSA (Specific Surface Area)
- Highly conductive
- Mass production available
- Cost competitive

Applications

≫TIM for EV Battery

≫TIM for Electronics & Automobile

New plant in Jecheon now under construction
for the future market expansion of TIM and Si/rGO anodic composite material

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