The Sixteenth International Conference
on the Science and Application of Nanotubes
Nagoya University, Nagoya, Japan, June 29 - July 3, 2015

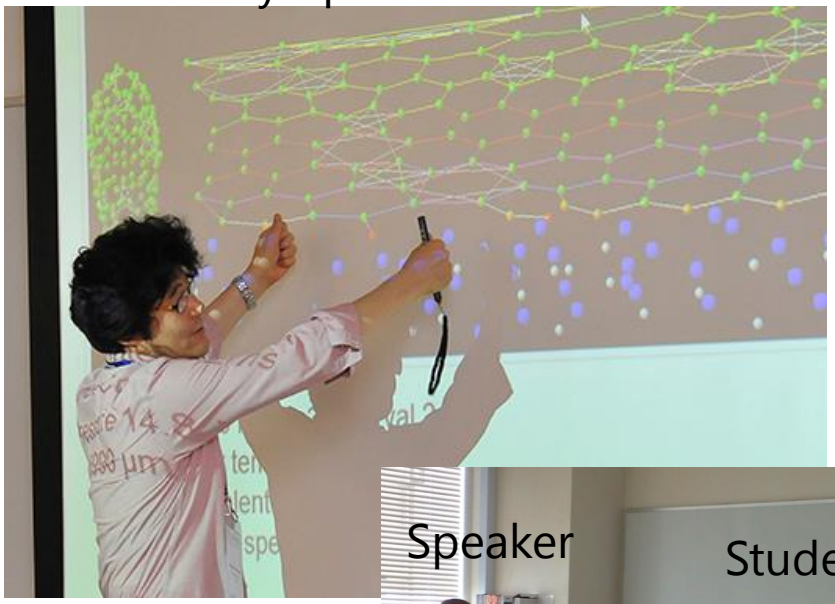
Conference Summary for NT 15

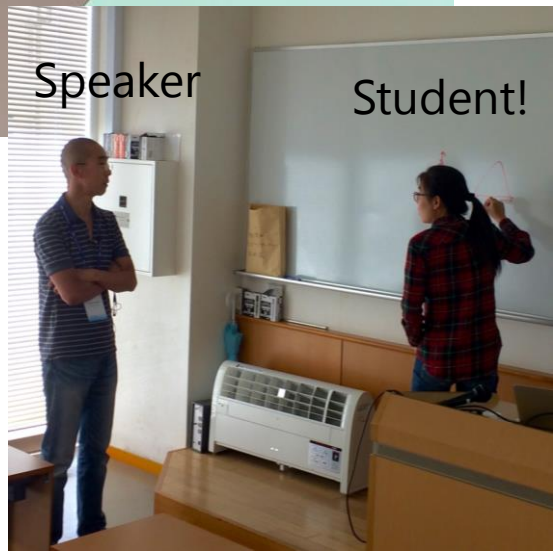
M. S. Dresselhaus, MIT

Nagoya, Japan July 3, 2015

On Sunday

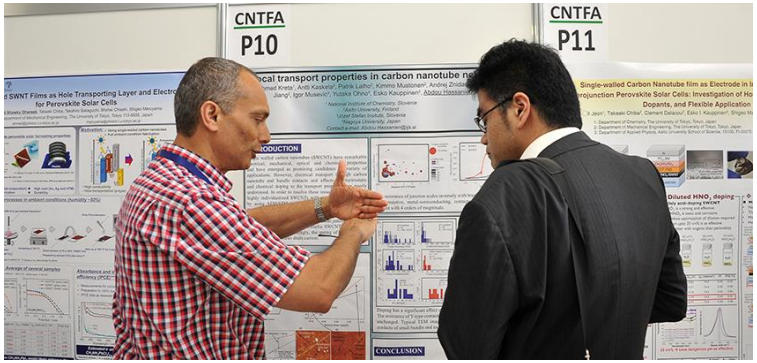
5 satellite symposia and 2 tutorials.

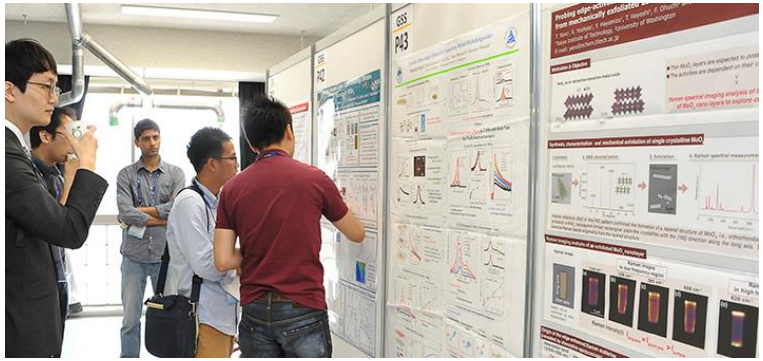




In an informal environment, sometimes the student teaches the speaker!

Welcome reception

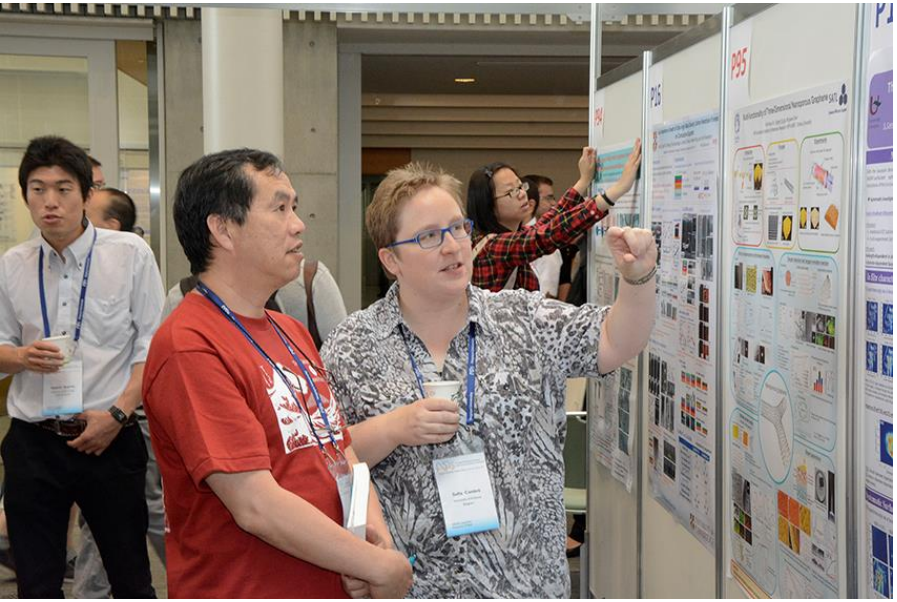




- NT 15 conference started.

Oral talks

Poster sessions



Company booths

Excursion

Lunchtime

Carbon fiber ⟶

Banquet

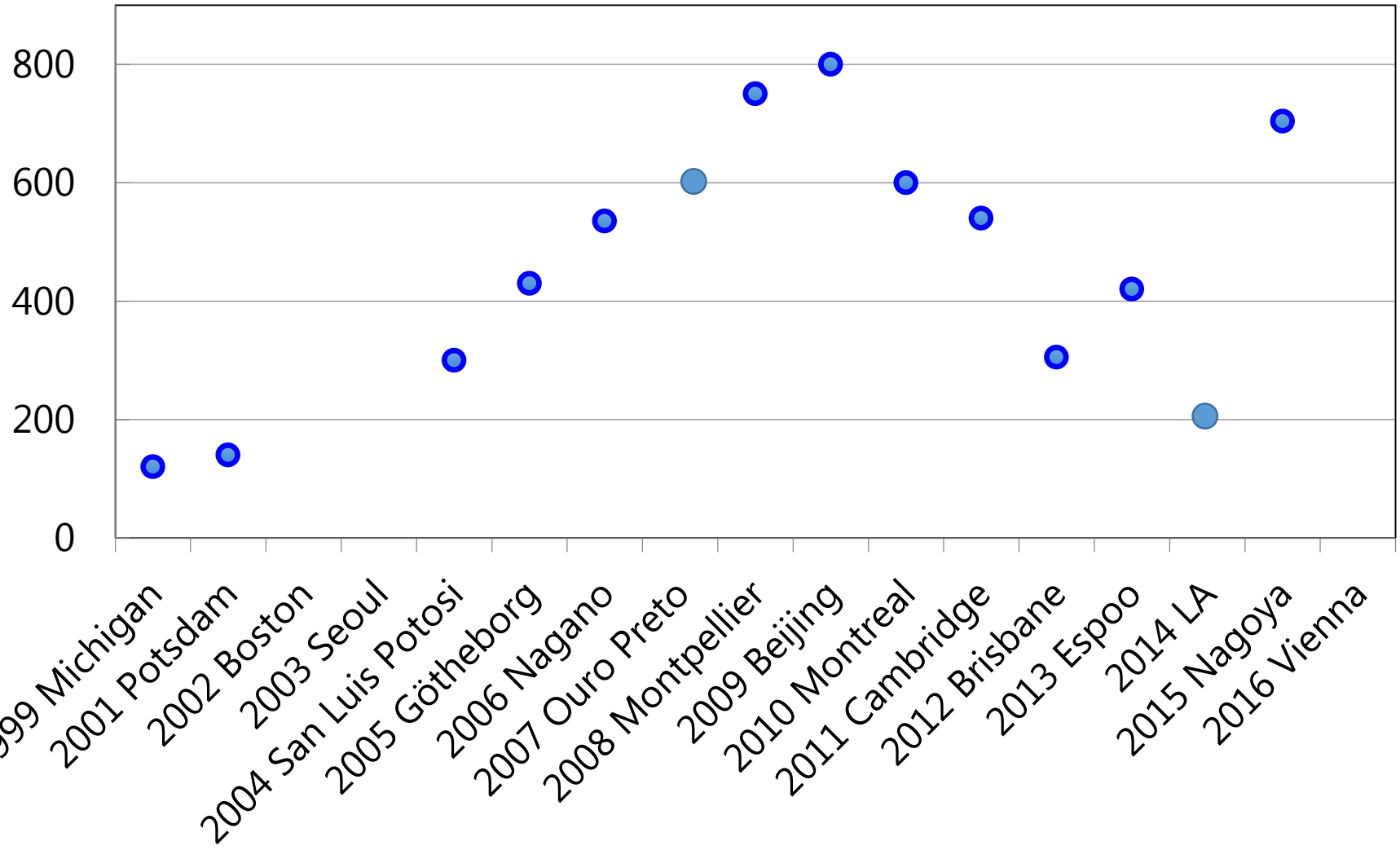
Statistics in NT 15

- **34 Oral presentations**
  - Keynote (5)
  - Invite talks (12)
  - Contributed talks (17)
- **520 Poster presentations**

with..

- 704 participants from 33 countries
- 5500 coffee break snacks served
- 3000 glasses of water served
- 300 original T-shirts sold out

Number of participants



- Materials science advances made in the last 10 years have been phenomenal!
- Exciting time to be researching nanotubes… but many don't know this!!!
- We need to collectively better communicate these advances and excitement to our peers …

THE HYPE CYCLE

Hype is common to new technologies. The market analysis firm Gartner developed its so-called hype cycle to represent how hype and technology evolve together. C&EN has selected a handful of events to illustrate this cycle for nanotubes. Because nanotubes have potential in many applications, the events are not necessarily chronological.

VISIBILITY

MATURITY

TECHNOLOGY TRIGGER

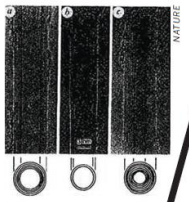
PEAK OF INFLATED EXPECTATIONS

TROUGH OF DISILLUSIONMENT

SLOPE OF ENLIGHTENMENT

PLATEAU OF PRODUCTIVITY

1991
Sumio Iijima brings nanotubes to the attention of the scientific community (*Nature* 1991, DOI: 10.1038/354056a0).

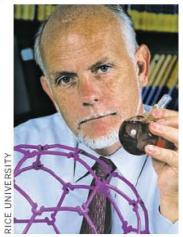


Nanotube micrographs.

1998
Researchers create the first nanotube transistor that works at room temperature (*Appl. Phys. Lett.* 1998, DOI: 10.1063/1.122477).

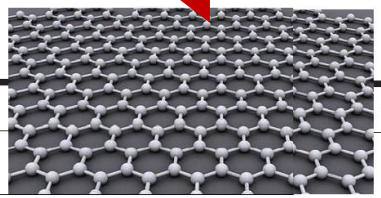
1999
Samsung researchers build a display using carbon nanotubes, leading some to speculate that nanotubes will be the next big thing in TV (*Appl. Phys. Lett.* 1999, DOI: 10.1063/1.125253).

Samsung's nanotube display.



1995
Richard E. Smalley's team at Rice University develops a method to grow high-quality single-walled tubes (*Chem. Phys. Lett.* 1995, DOI: 10.1016/0009-2614(95)00825-O).

2004
With the isolation and characterization of graphene, research… invested in nanotubes investigating new ma… (*Science* 2004, DOI: 1… science.1102896).

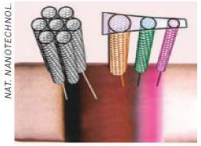


A sheet of graphene.

ALEXANDERAIUS/ WIKIMEDIA COMMONS

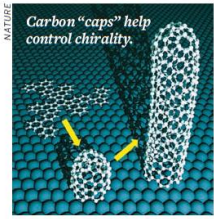
2006
Scientists separate nanotubes by their electronic properties, an important step toward advanced nanotube electronics (*Nat. Nanotechnol.* 2006, DOI: 10.1038/nnano.2006.52).

2013
Bayer MaterialScience shuts down its nanotube production operations.



Nanotubes separated in water.

2011
NASA launches the *Juno* satellite, which makes use of protective nanotube composites.

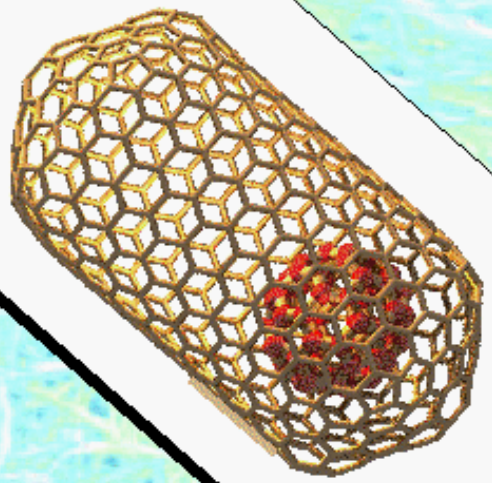


2014
Two separate groups report techniques for growing homogeneous nanotubes. (*Nature* 2014, DOI: 10.1038/nature13434 & DOI: 10.1038/nature13607).

NT99

NANOTUBE-99

http://www.pa.msu.edu/conf/nt99/



INTERNATIONAL WORKSHOP ON THE

SCIENCE & APPLICATION OF NANOTUBES

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

MICHIGAN STATE UNIVERSITY

Organizers:

David Tománek
Michigan State University
Richard J. Enbody
Michigan State University

Purpose:

Nanotube Technology:
The Present and the Future

An open discussion forum including
Physicists, Chemists, Engineers involved
in Nanotube Research

Invited Speakers Include:

Phaedon Avouris, *IBM*
Jerzy Bernholc, *NCSU*
Patrick Bernier, *Univ. Montpellier*
Jean-Christophe Charlier, *Univ. Louvain*
Walt De Heer, *Georgia Tech* *
Cees Dekker, *TU Delft*
Mildred and Gene Dresselhaus, *M.I.T.*
Peter Eklund, *Kentucky*
John E. Fischer, *Pennsylvania*
Laszlo Forro, *EPFL*
Jisoon Ihm, *Seoul*

NT conference series, Since 1999

NT15

SATL Science of Atomic Layers

Participants increased

NT'01(2nd) in Potsdam

NT'09(10th) in Beijing

NT’15 in Nagoya

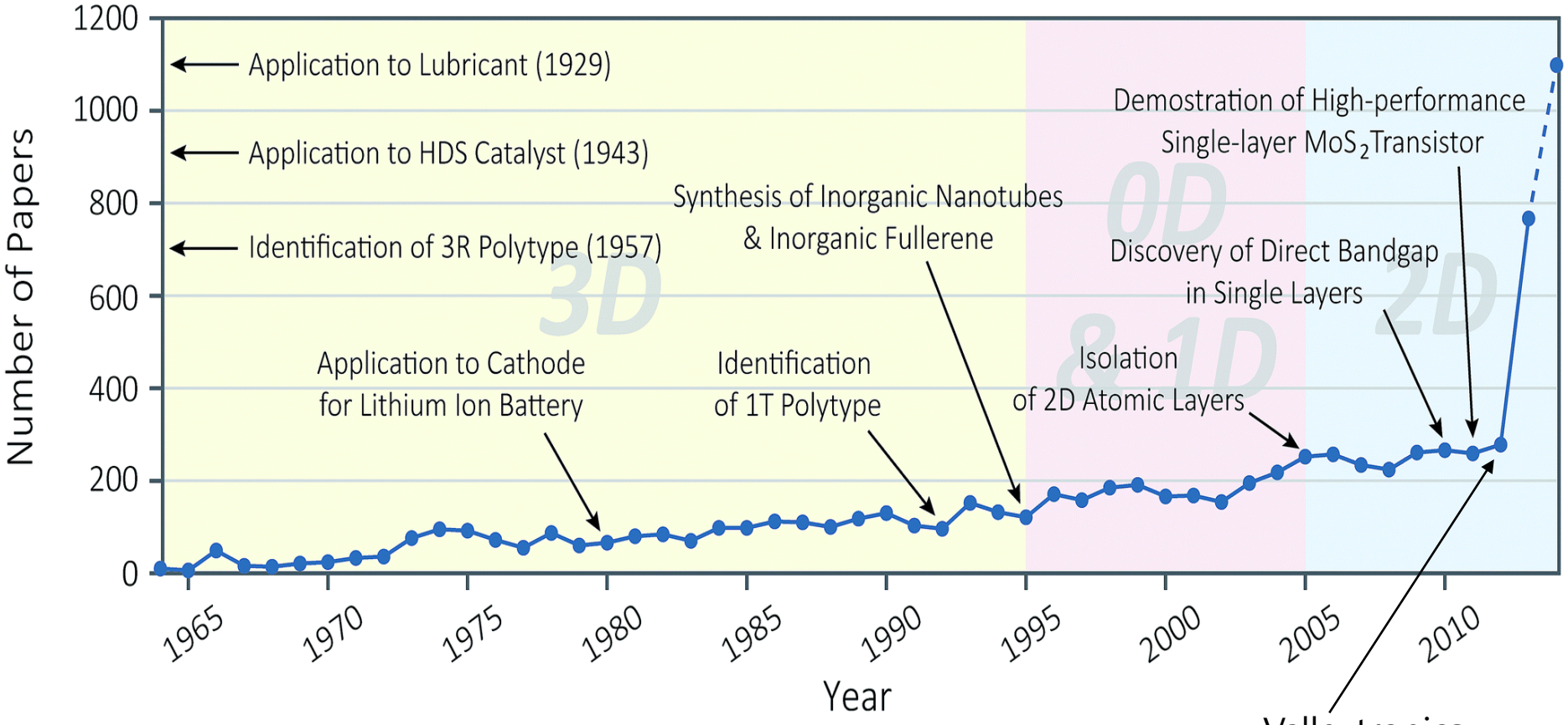
Statistics on titles of 520 posters in NT15

Materials	
Nanotube nanotube(s), SW(C)NT(s), MW(C)NT(s), CNT(s),	323
Graphene graphdyine, graphyne, nanocarbon sheet, etc.	140
Others (not including above words)	81

Different structures:	Aerographite, porous, pores, foam, sponge	14
	Fullerene, C60	11
	Nanohorn 2, Nanofiber 3, Nanowall 4 Diamond 3, nanocross 1, nanopot 1, graphite 8	
Non carbon:	BN, boron nitride	11
	Dichalcogenides, diselenides, WSe_2, MoS_2, ditelluride, disulfide,	25
	Phosphorene, phosphorus	6

THE IMPACT OF CNTs on LOW DIMENSIONAL MATERIALS SCIENCE

History of MoS_2 research

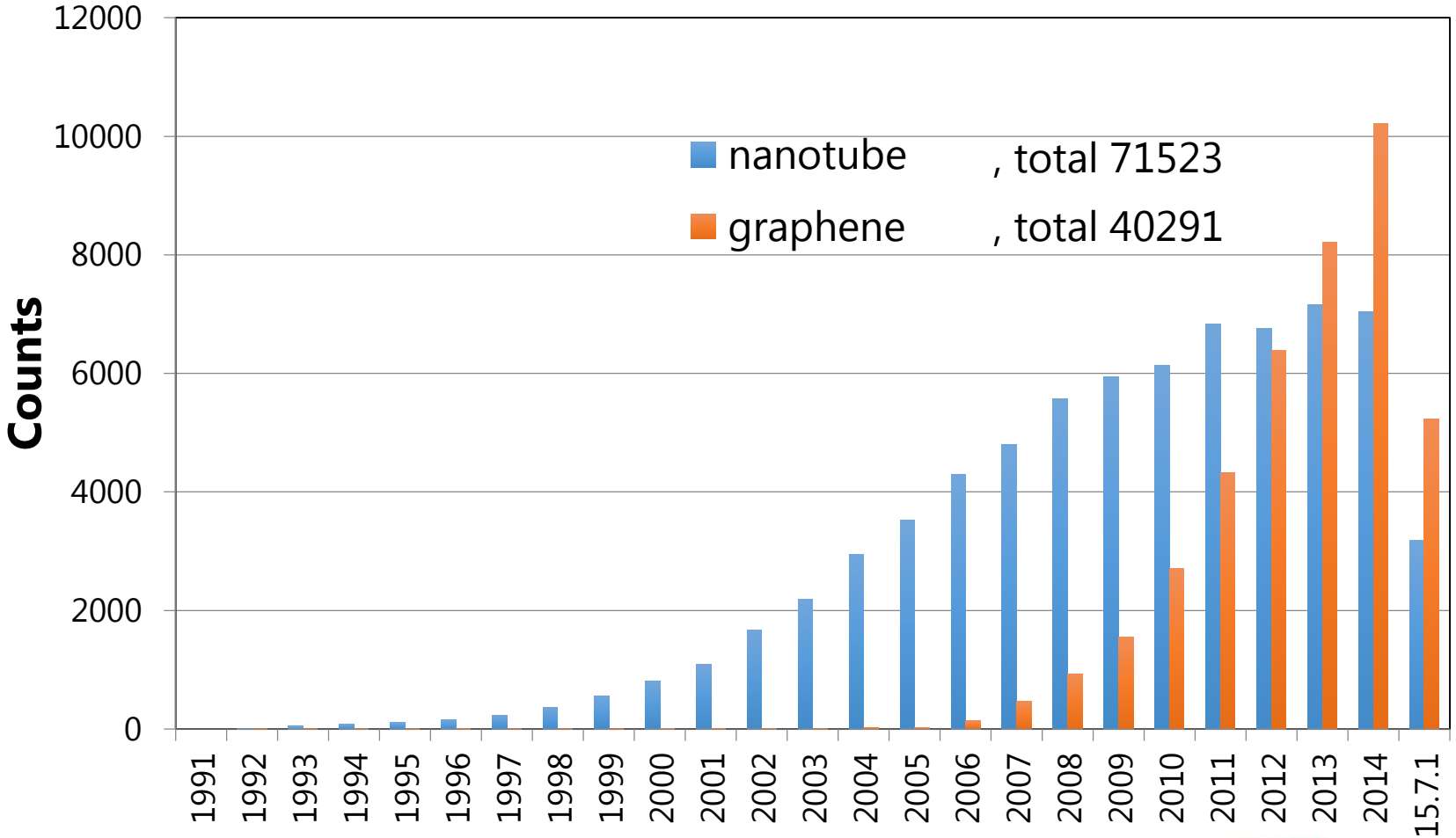


Similar history for Phosphorene

(Thank you David Tomanek!)

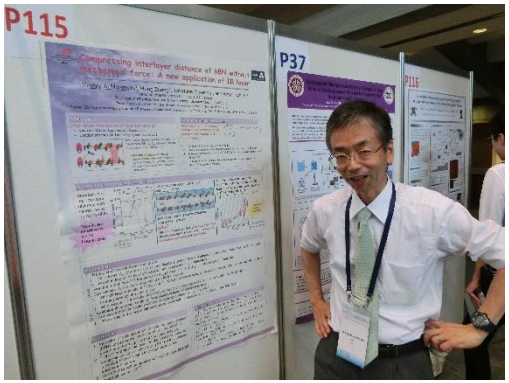
I. Song et al., RSC Adv. **5**, 7495 (2015)

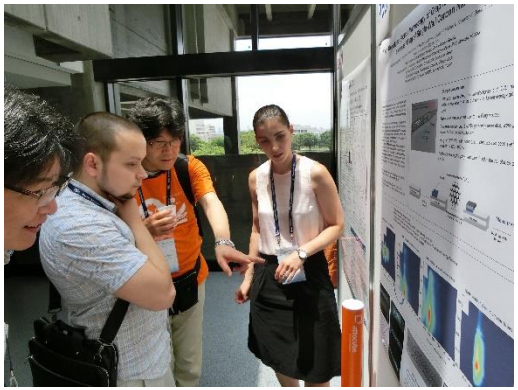
Numbers of publications including “nanotube*” and “graphene*” in title (searched by web of science, since 1991)



Uniqueness of NT conferences

- No parallel sessions
- Large # of posters
  - Students and professors both present posters
  - Poster summaries guide individual selection
  - Promote person-to-person contact
- Emphasis in new science and new low dimensional materials





Scientific outcome

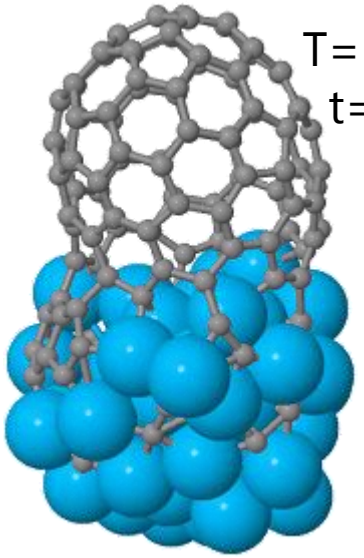
- **Satellite symposia (June 27)**
  5 symposia and 2 tutorials

- **NT15 (June 28-July 3)**

Satellite symposia

- **CNTFA15: CNT Thin Film Electronics and Applications**
  Above 70 attendees; 15 oral talks + 27 posters.
- **CCTN15: Computational Challenges and Tools for Nanotubes**
  Under 50 attendee; 22 presenters
- **MSIN15: Metrology, Standardization and Industrial Quality of NTs**
  13 talks + 10 posters
- **GSS15: Graphene and 2D Materials**
  160 Registrations; 18 Oral talks + 60 Posters
- **CNBMT15: Carbon Nanomaterials Biology, Medicine & Toxicology**
  41 attendees

- **Scope: Quantitative understanding of physical properties**
- **Main results: SWCNT growth**
  (~30% of presentations!)
- **Future impact: Showing a path forward for improving synthesis**



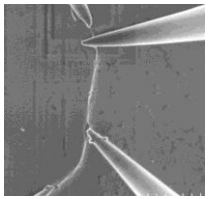
Starting to bridge the gap between experiments and simulations (Neyts).

From → **Accuracy** in well established protocols
To → **New methods** for **single events** in **single CNT units**

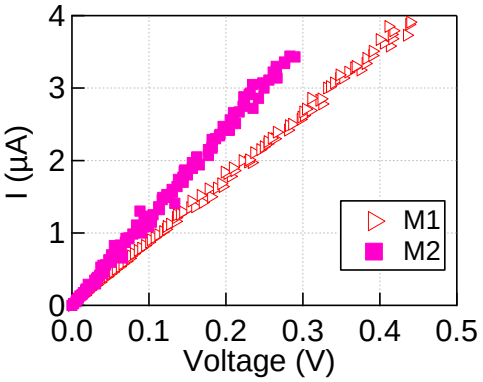
From ***To***

Resistance

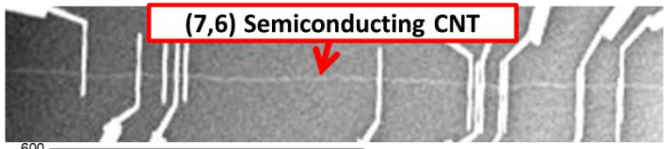
Certified protocols for 4-probe resistance

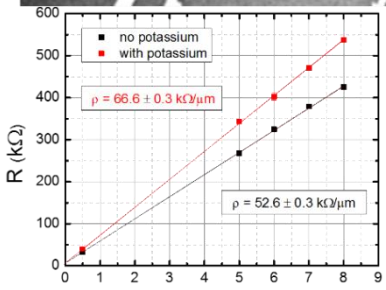


by H. Akinaga



R added by one K atom





Resistivity added by K atoms
14.0 ± 0.6 kΩ/μm

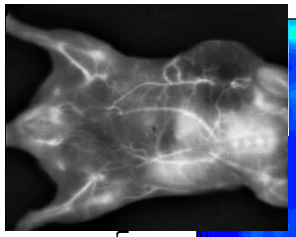
9 ± 2 K atoms / μm

Resistance of each K atom
1.6 ± 0.4 kΩ

by M.Ishigami

Optics

Application as fluorescent probes

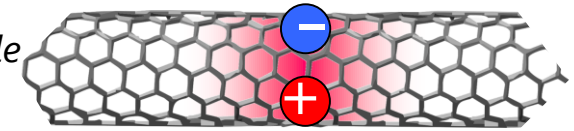


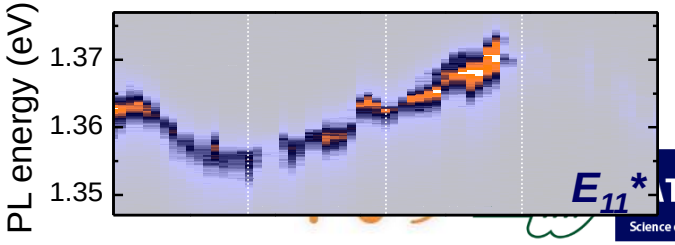
UV/O_3 irradiation
(Epoxide-CNT)

by T.Okazaki

Single defect-localized exciton

by A. Högele





CNTFA15 –CNT Thin Film Electronics and Applications

Scope: CNT thin applications in touch sensors, displays, integrated circuits, optics and energy production like e.g. solar cells.

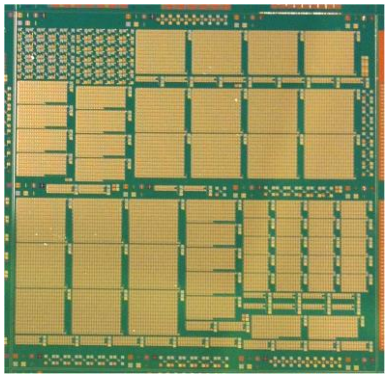
Main results:

Transistors: Improved uniformity (possibly <5%), Hybrid CMOS of SWNT/IGZO

Transparent conductors: Flexible/moldable touch sensors

Emerging applications: Optoelectronics, Solar cells, THz detectors

Interconnects: Robust SWNT-Cu composites



SWNT/IGZO hybrid **LSI** (**>1,000 FETs**, USC)

CNBMT15– Carbon Nanomaterials Biology, Medicine & Toxicology

Scope: Specific applications in the biomedical fields

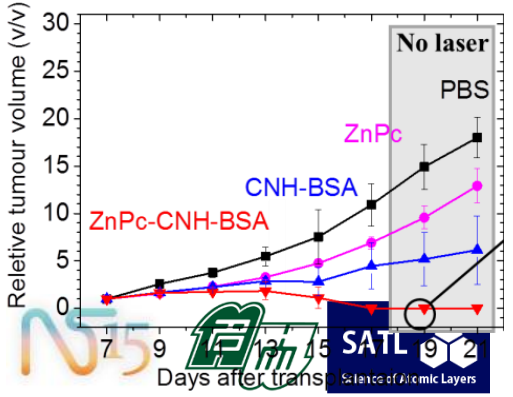
Medical functions: Remote thermal therapy

Future impact: - Practical medical treatments

- New theranostic systems

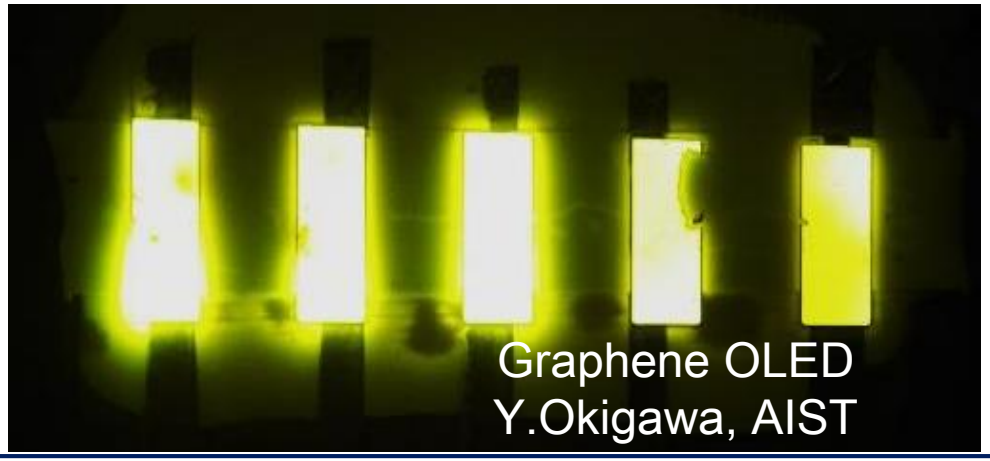
⇒Early findings and treatments of diseases

Laser therapy



GSS15-Graphene and 2D

- **Materials:**
  Graphene, h-BN, MoS_2, WS_2, WSe_2, Black Phosphorus, B_4C
- **Results:**
  Organic LED, Black phosphorus device, TEM, Raman spectroscopy, Synthesis, etc.
- **Future impact:** Boost of the information exchange between a broad spectrum of 2-dimensional materials



NT15 conference
Main subjects in oral presentations

- Monday, History and new 2D
- Tuesday, Advances in (n,m) synthesis, sorting
- Wednesday, From synthesis to applications
- Thursday, More applications
    - (New) Panel on “Applications of CNTs”
- Friday, “Dreams come true”

Monday summary

- **Carbon nanotubes**
  - **History: Reviewing the past is learning something new!**
  - **Adsorbate-CNT interaction**
  - **Simple and high speed separation**

- **Graphene**
  - **In-situ observation of growth**
  - **Preferentially formation of zigzag edge**
  - **For cancer therapies**

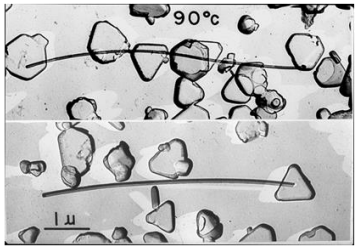
- **Transition metal dichalcogenides**
  - **Quantum Phenomena in Field Effects**
  - **Hetero-structures and Devices**
  - **Interlayer excitonic interactions**

Mon

History of carbon nanotubes

- **History (S. Iijima)** **Reviewing the past is learning something new!**

Ag filaments (1968)



Old

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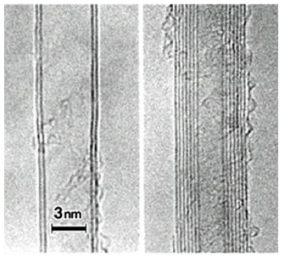
on ko chi shin

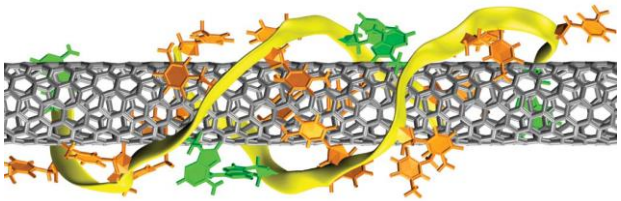
carbon nanotubes (1991)



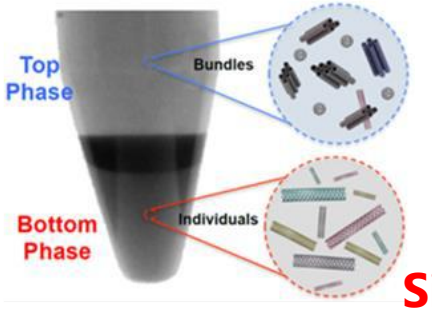
New

- **Adsorbate-CNT interaction (T. Hertel)**

Adsorbate-CNT interaction



- **Separation using Aqueous Two-Phase (N. K. Subbaiyan)**



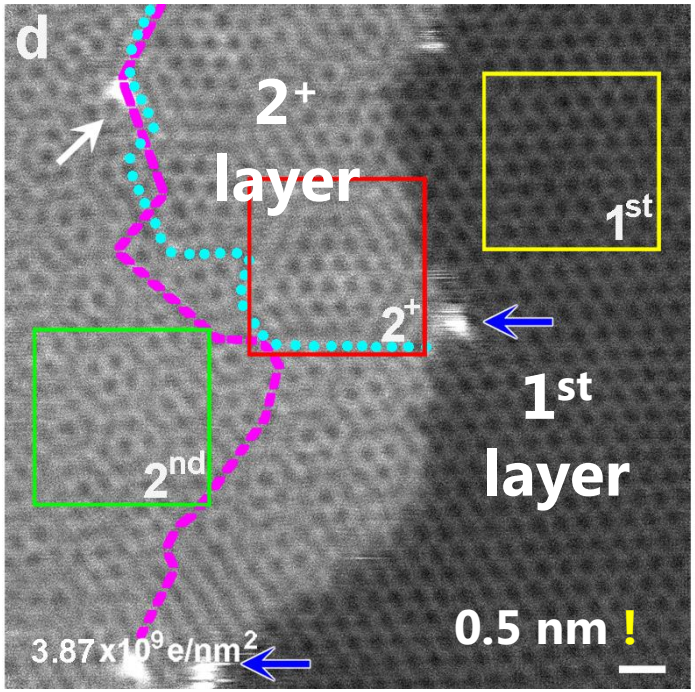
Simple and high speed !

Mon

2D (Graphene)

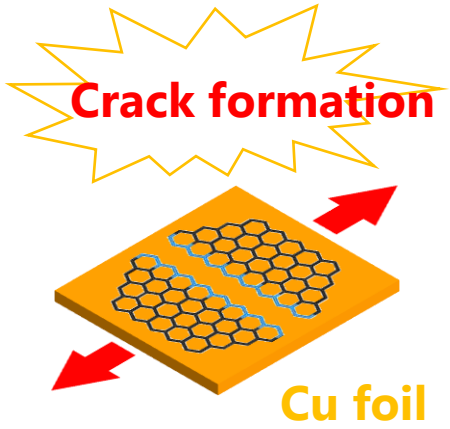
- **Atomistic evidence of step-edge growth**

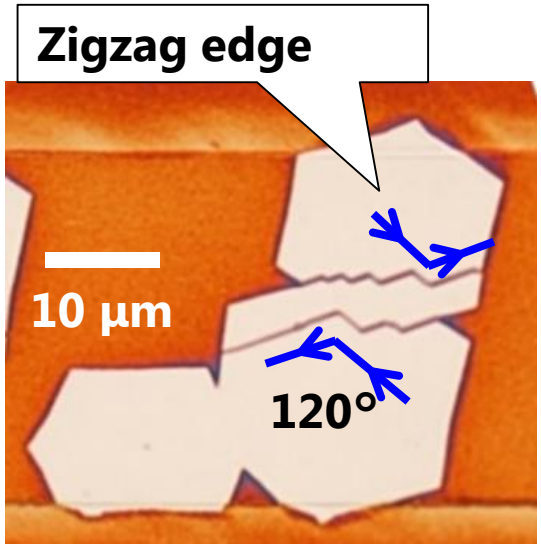
(Z. Liu)



- **Preferentially formation of zigzag edge in crack**

(M. Fujihara)





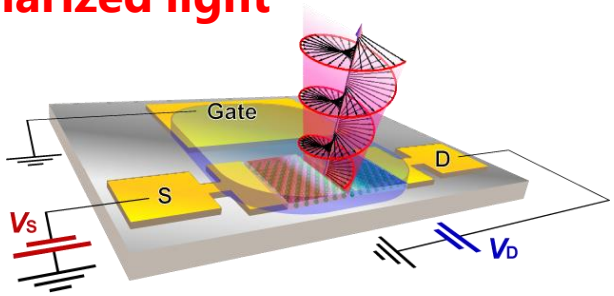
- **Medical application (A. Vijayaraghavan)- Graphene oxide for cancer therapies**

New 2D (Transition metal dichalcogenides)

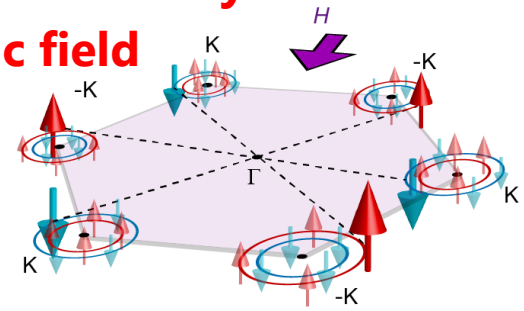
Mon

- **Quantum Phenomena in Field Effects (Y. Iwasa)**

EL: Circularly polarized light

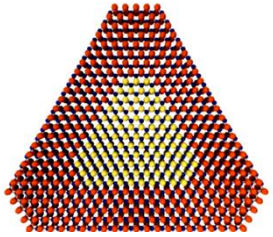


Robust superconductivity under magnetic field

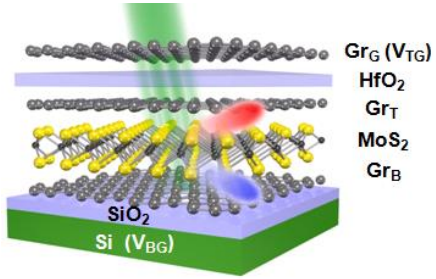


- **Hetero-structures and Devices (X. Duan)**

In-plane growth



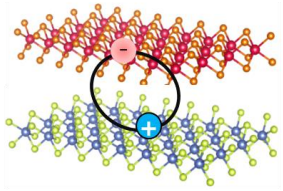
WS_2 - WSe_2



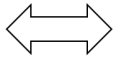
- **Optical properties (S. Mouri)**

***T* < 160 K**

Inter-layer exciton

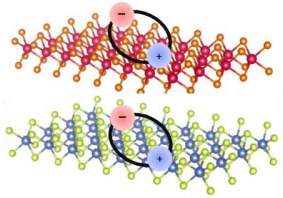


Thermal crossover



***T* > 160 K**

Intra-layer exciton



Tuesday summary

- **Electronics**
  - **CNTs and nanoribbons: transistors & photovoltaics**
  - **Logic Circuits, Memory, and Heterostructures**

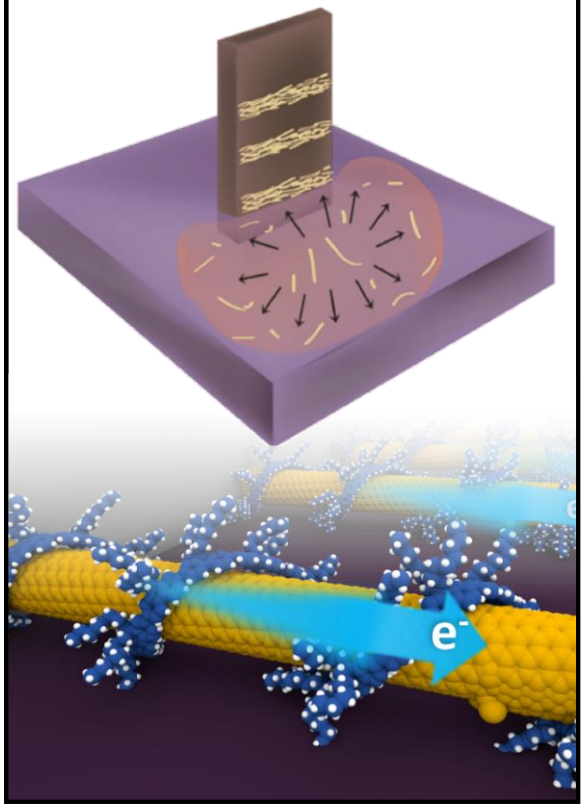
- **CNT growth**
  - **Selective Cloning**
  - **Dense and horizontally-aligned arrays using Trojan Catalysts**
  - **Simulation: from hydrocarbons**

- **Bridging materials with applications**
  - **Structure and Energetics of DWNT**
  - **Computational Approach to Electrical Contacts in CNT Transistors**

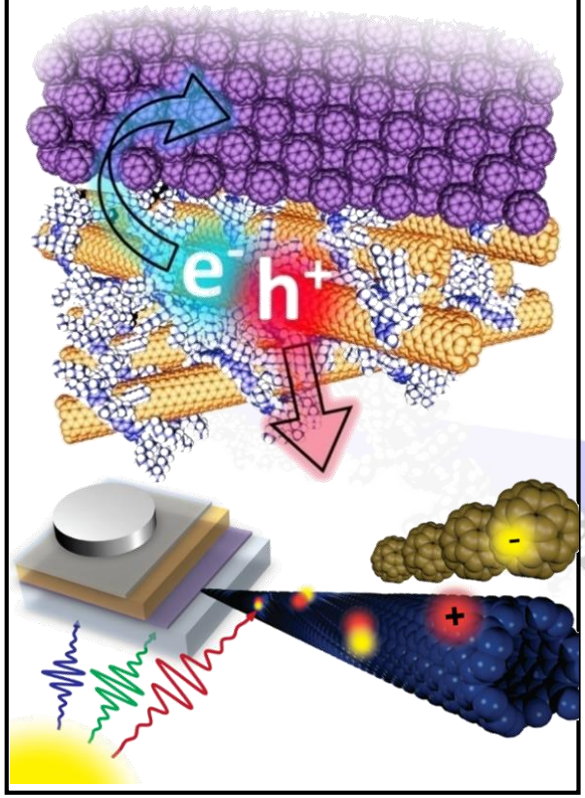
Overcoming historical challenges in carbon nanotubes and nanoribbons: Enabling transistors & photovoltaics (M. S. Arnold)

Tue

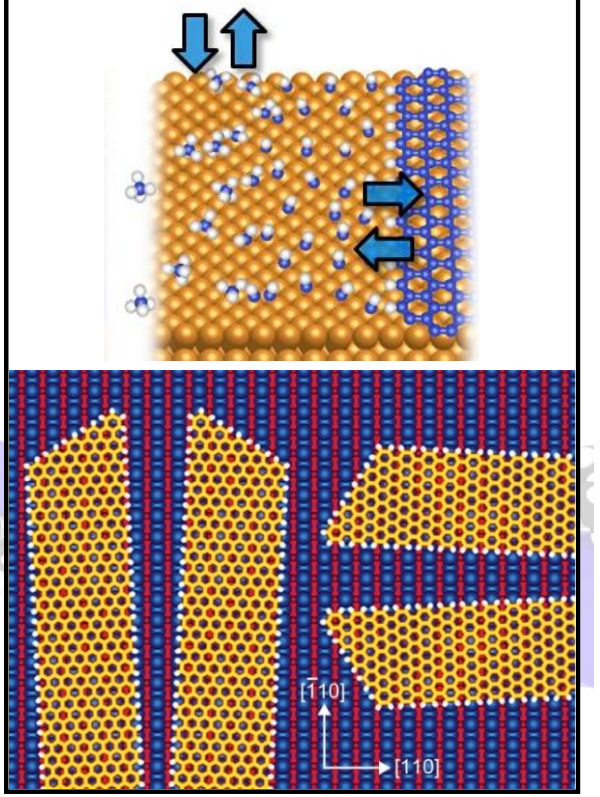
Sorting & aligning → high performance FETs



Nanotube photophysics and PV



Edge refined nanoribbons

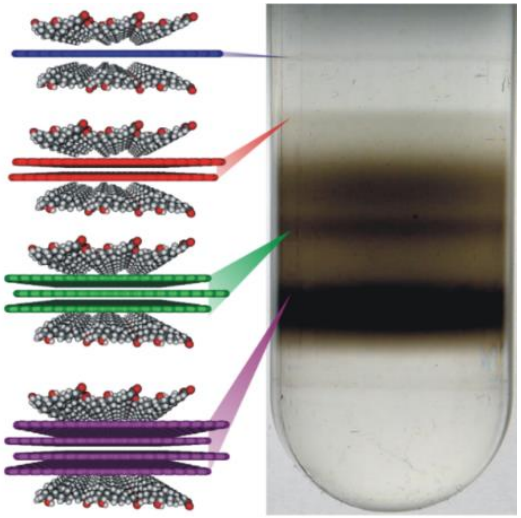


Beyond Carbon Nanotube Thin-Film Transistors: Logic Circuits, Memory, and Heterostructures

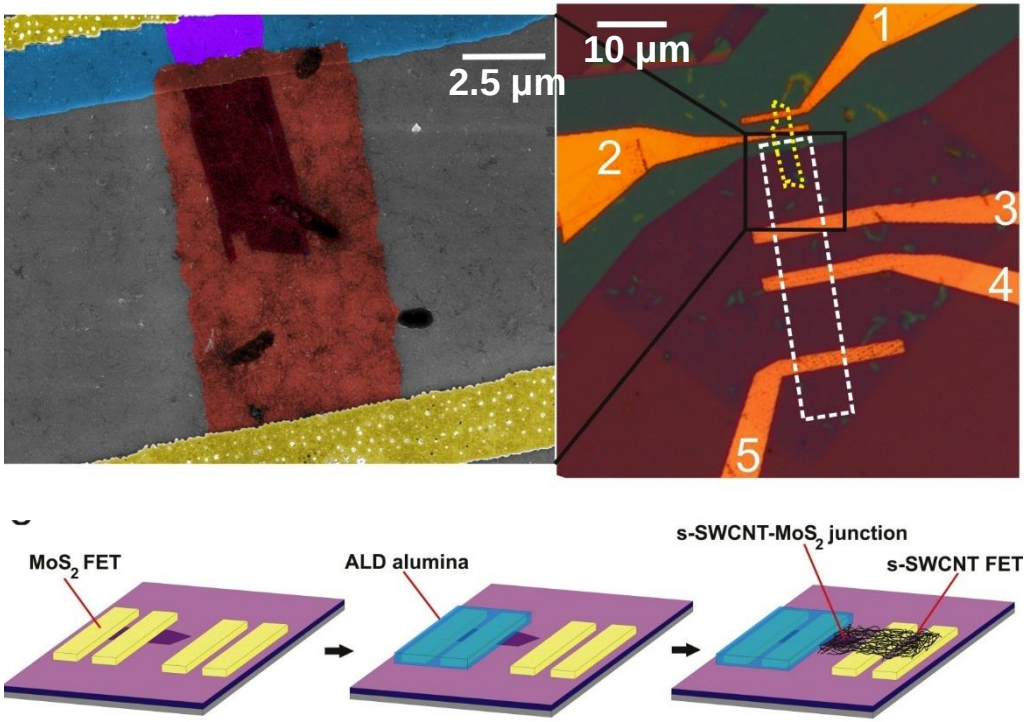
Tue

(M. C. Hersam)

Separation



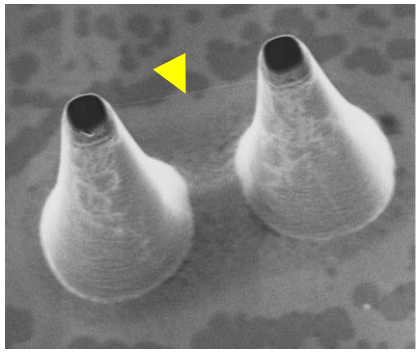
Heterostrucutre



CNT growth

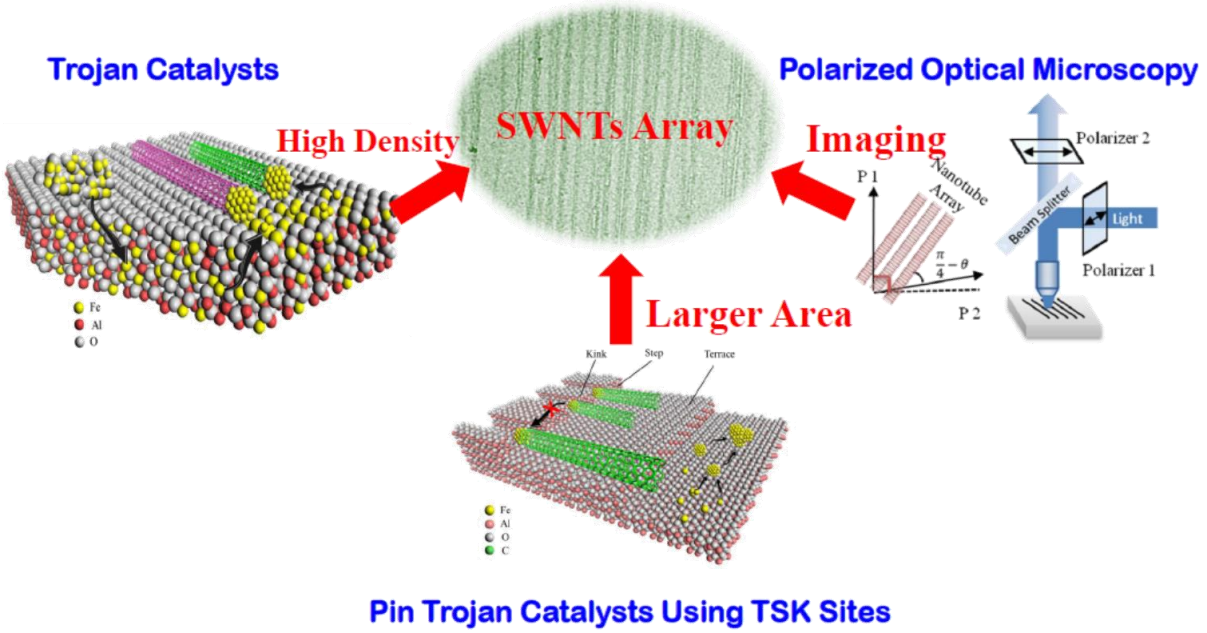
Tue

- **Selective Cloning**
  (Y. Homma)



(9, 4) CNT

- **Growth of High-Density Horizontally Aligned SWNT Arrays using Trojan Catalysts** (J. ZHANG)



Wednesday Summary

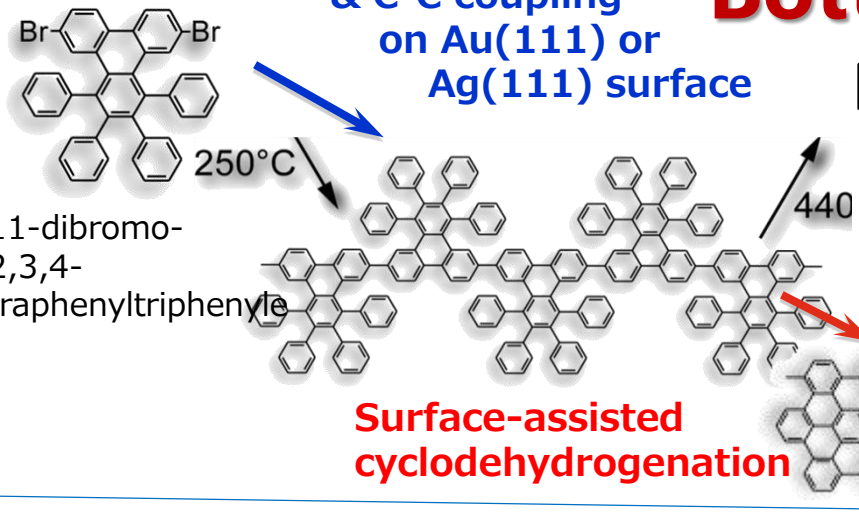
- **Controlled fabrication of GNRs and CNTs**
- **Energy harvesting**
- **Challenge to low-power devices**

Controlled fabrication of GNRs and CNTs

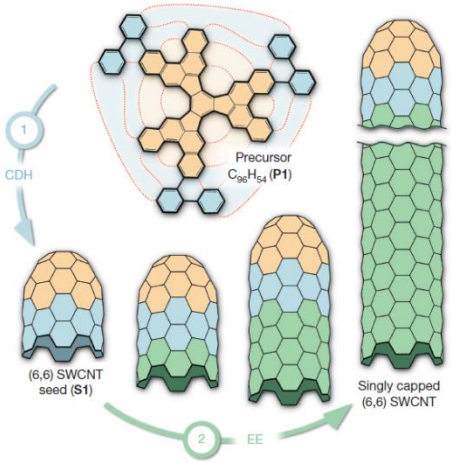
Bottom up

Roman Fasel

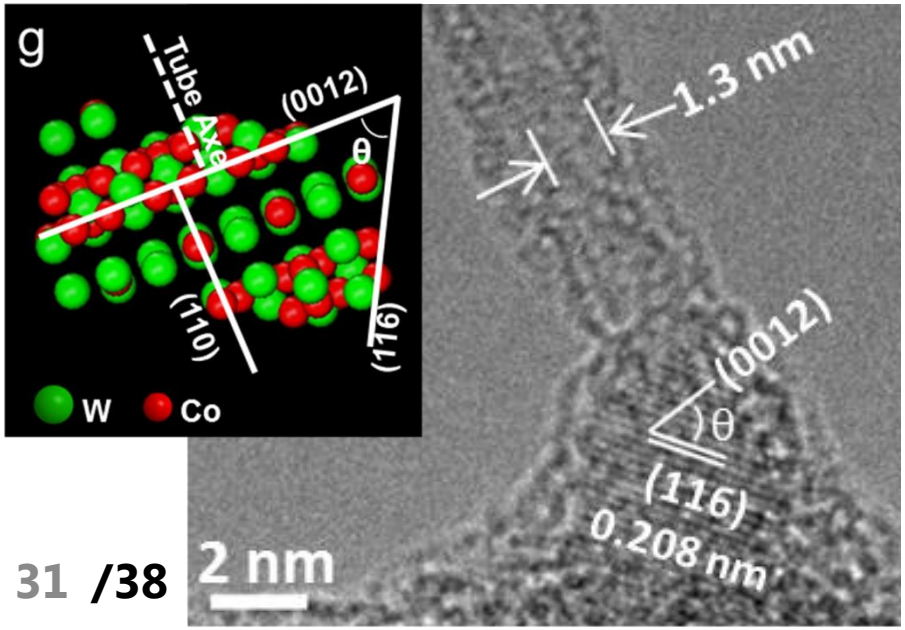
Dehalogenation & C-C coupling on Au(111) or Ag(111) surface



6,11-dibromo-1,2,3,4-tetraphenyltriphenylene



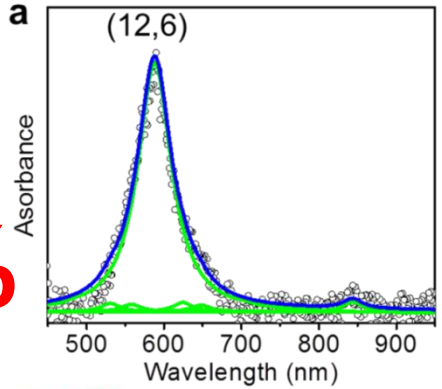
Chirality control



Catalyst used to control (n,m) using CVD

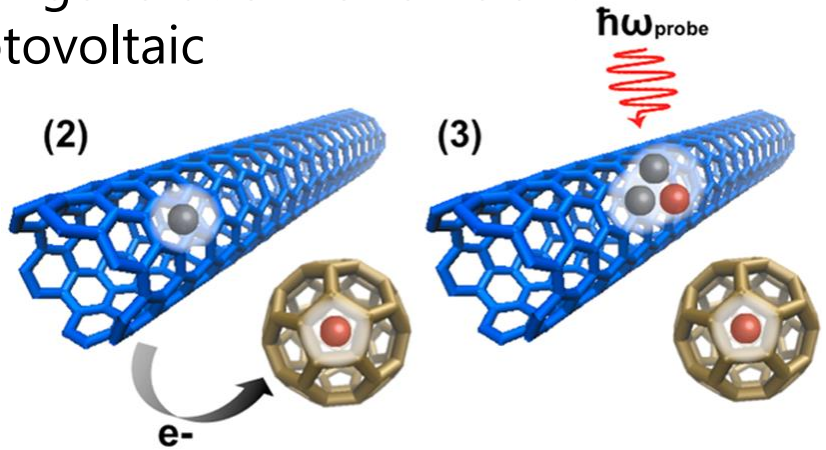
Yan Li

92.5%



Energy harvesting (Jeff Blackburn)

Trion generation for efficient photovoltaic



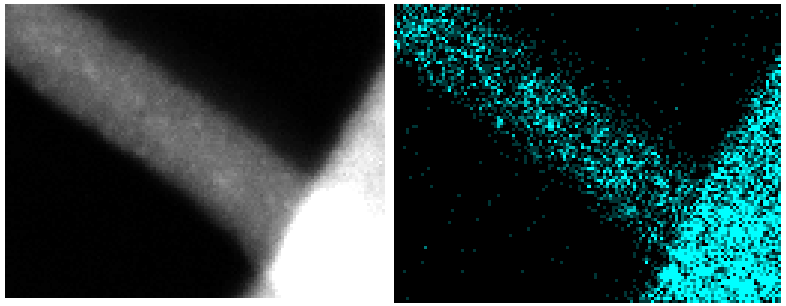
Thermoelectrics

$$ZT = \frac{S^2\sigma}{\kappa}T$$

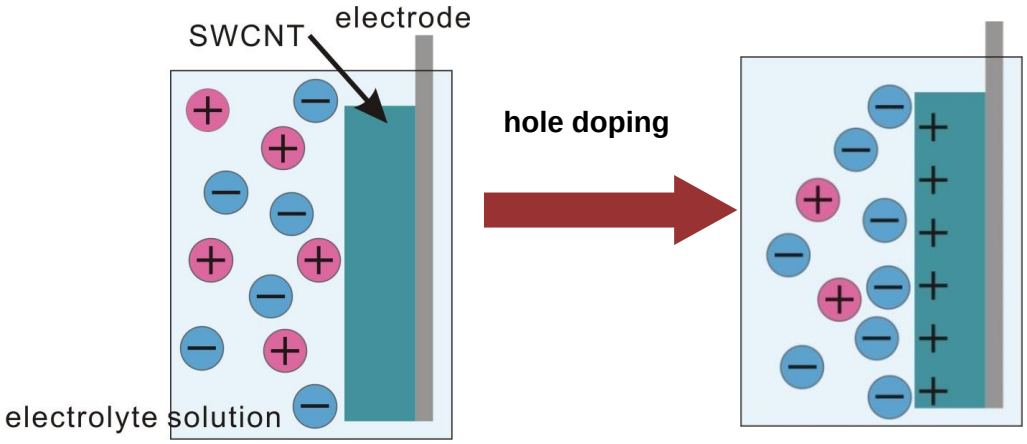
Controlled doping of s-SWCNTs

- Best α ≈ 600 - 2500 μV/K
- Best σ ≈ 2 x 10^5 S/m
- Best PF ≈ 350 μW/mK^2

Other approaches for thermoelectrics

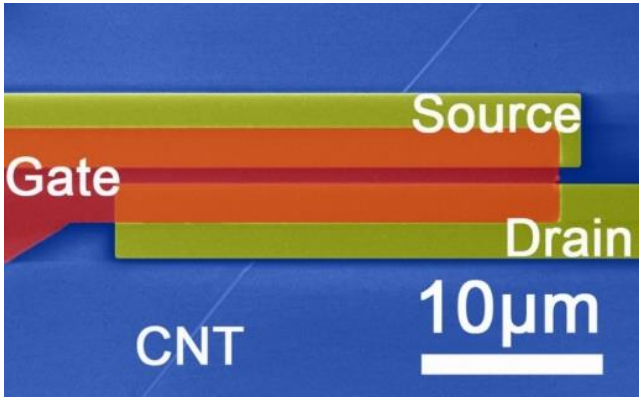


Co encapsulation for ***stability***
Tsuyohiko Fujigaya



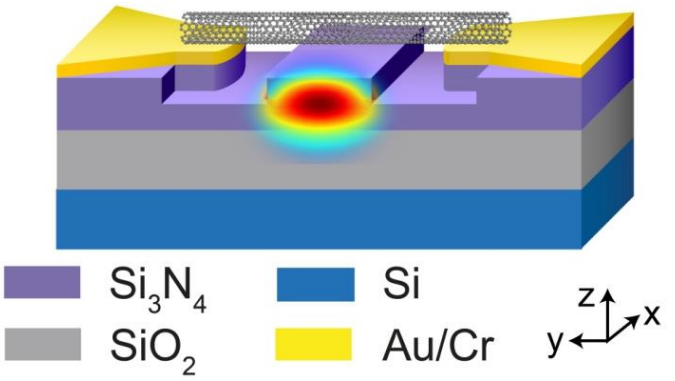
Electrochemical doping to ***vHS***
Kazuhiro Yanagi

Challenge to low-power devices

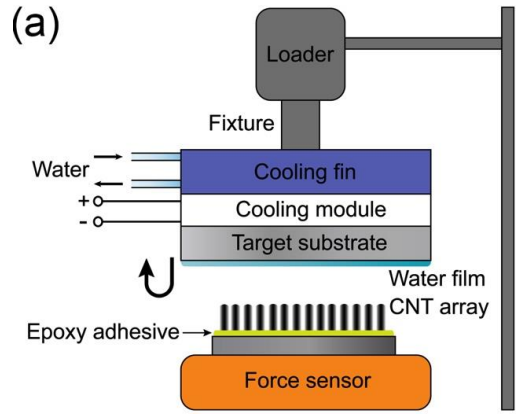


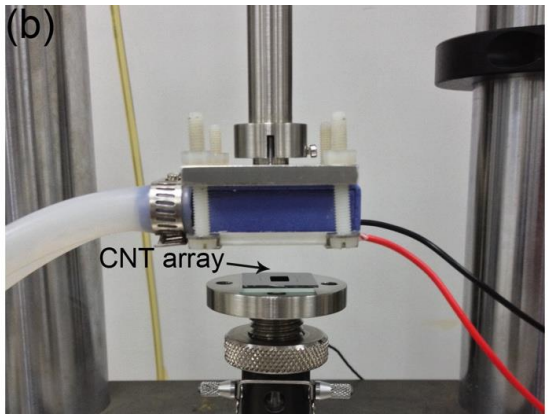
Ballistic CNTFETs !
Lian-Mao Peng

LED with photo-resonator
Felix Pyatkov



Ice assisted transfer for CNT field emitter Yang Wei

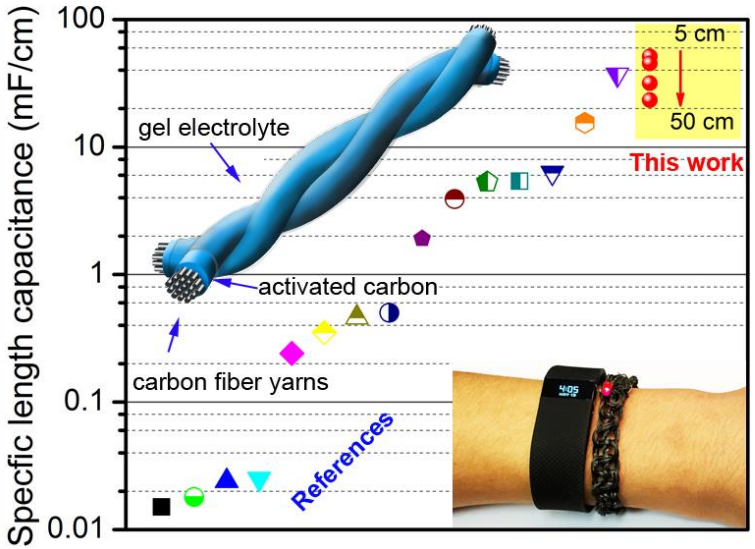




Thursday summary

- **Flexible devices**
- **Panel on “Application of CNT”**

Flexible devices

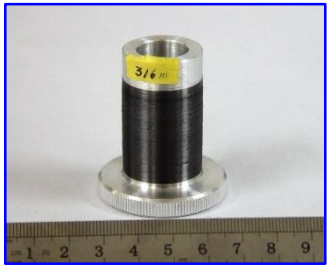


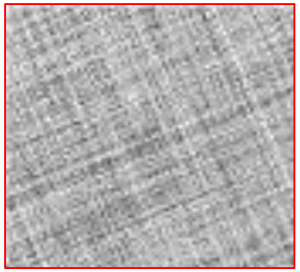
Yarn hybrid carbon fiber for super capacitor
Yuan Chen

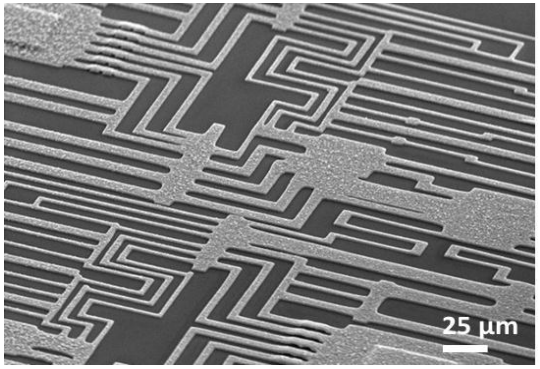
Panel on “Application of CNT”

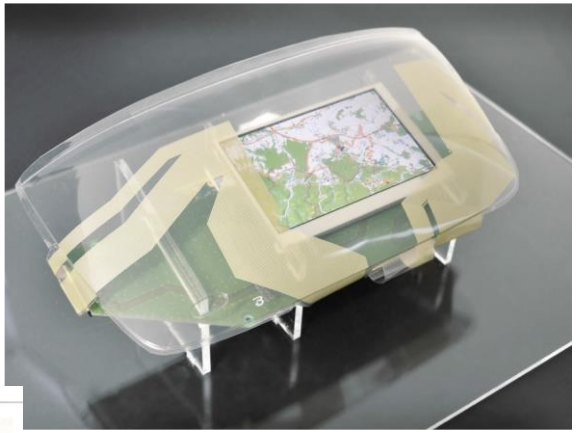
7 panelists discuss

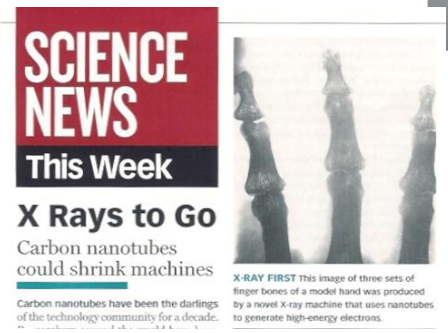
Laboratory → Startup company → Mass production

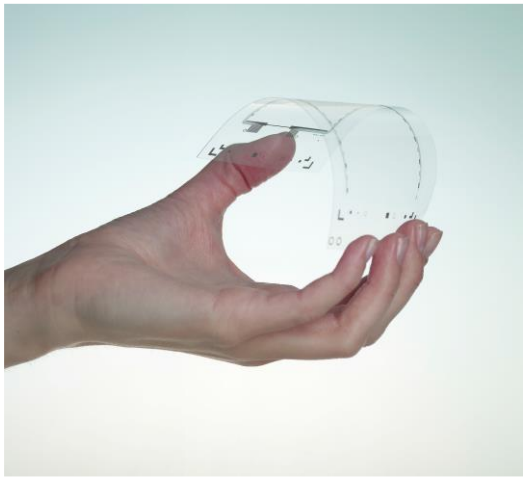






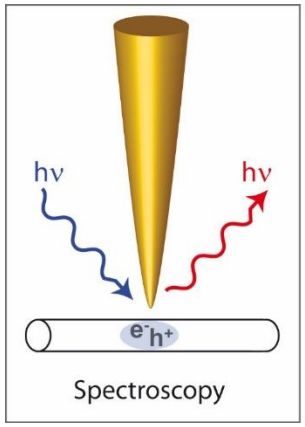


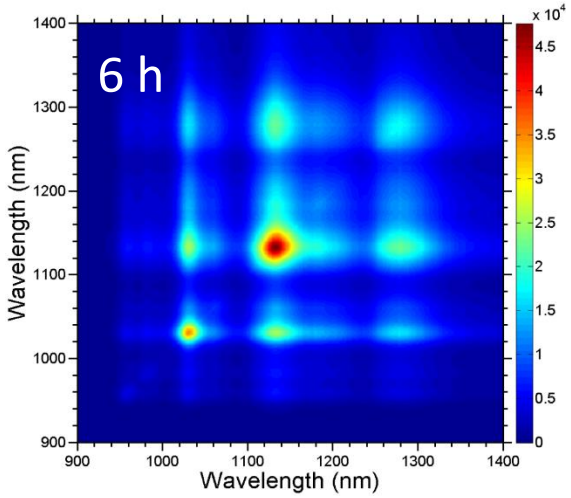


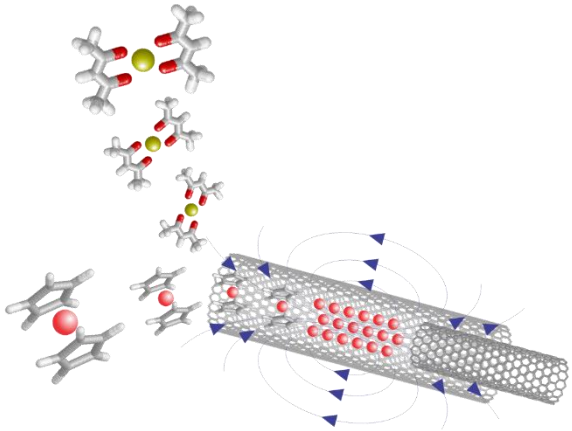


Friday summary

- (D. Tomanek) Nanotube dreams
- (A. Hartschuh) High-Resolution Near-Field Optical Microscopies
- (R. B. Weisman) Variance Spectroscopy
- (T. Pichler) Tailoring 1D and 2D nanocarbons
- (L. Shi) Ultra-long carbyne @DWCNT







Looking to the future

- Role of NTxx conference series has been unique.
- What should be the future direction of NTxx?
- Looking into the past is important to envision the future.

Extra slides

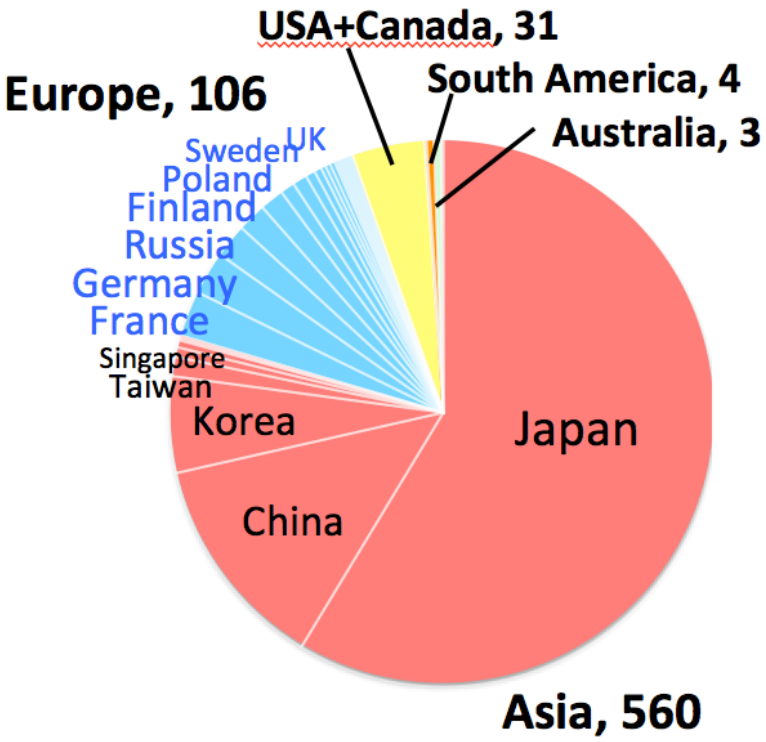
Q Role of metrology and theory

- Do we need to concern a *practical* situation?
  - To know what is going on throughout growth
  - To know what is going on throughout device operation
- Or do we need to concern *ideal* situation?
  - To know principles of growth
  - To know principles of device operation
- Concerning both of above for deciding next directions

Country of participants

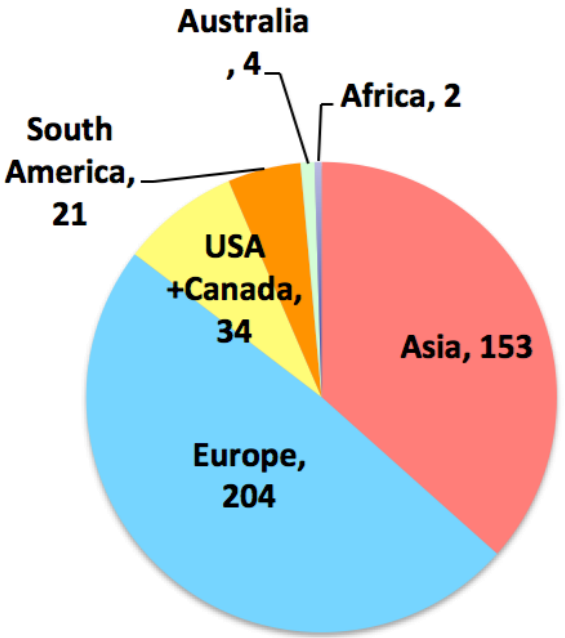
NT15, Japan

33 countries, 704 participants



NT13, Finland

37 countries, 430 participants



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Purpose of NT conference series is,

(from Charter of the NT Conference Series)

- **To promote scientific progress**
- **To stimulate free exchange of ideas**
- **To publicize progress in nanotube sciences.**