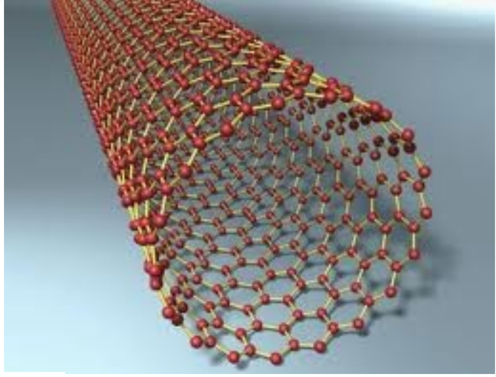
Aalto University

IRENA
Indium Replacement by Single-Walled Carbon Nanotube Thin Films



Japan Science and Technology Agency

IRENA project: Indium replacement by single-walled carbon nanotube thin films

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The University of Tokyo, Tokyo, Japan

February 25th, 2015

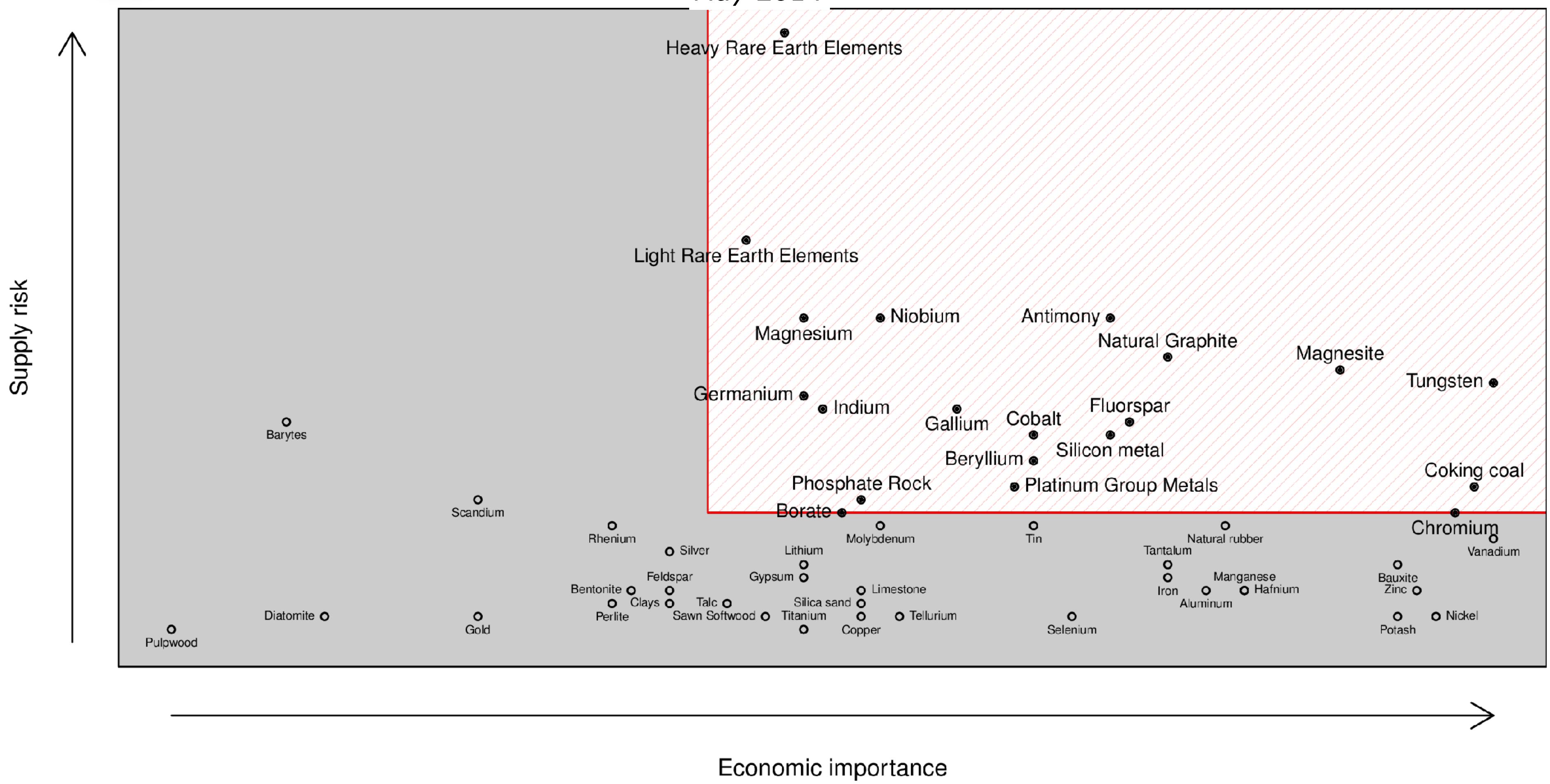
Content

- **The need** to replace Indium and Gallium in transparent conductors (TCF) and thin film transistor (TFT): carbon nanotubes as novel materials for flexible, transparent and stretchable electronics ?
- **Project objectives**: meet ITO (indium-tin oxide) TCF and IGZO (indoum-zinc-gallium oxide) TFT specs with flexible SWNT thin films
- **Partners**: 3 from EU and 3 from Japan
- **Main results** for TCF, TFTs and solar cells
- **Future plans** – how to use the results

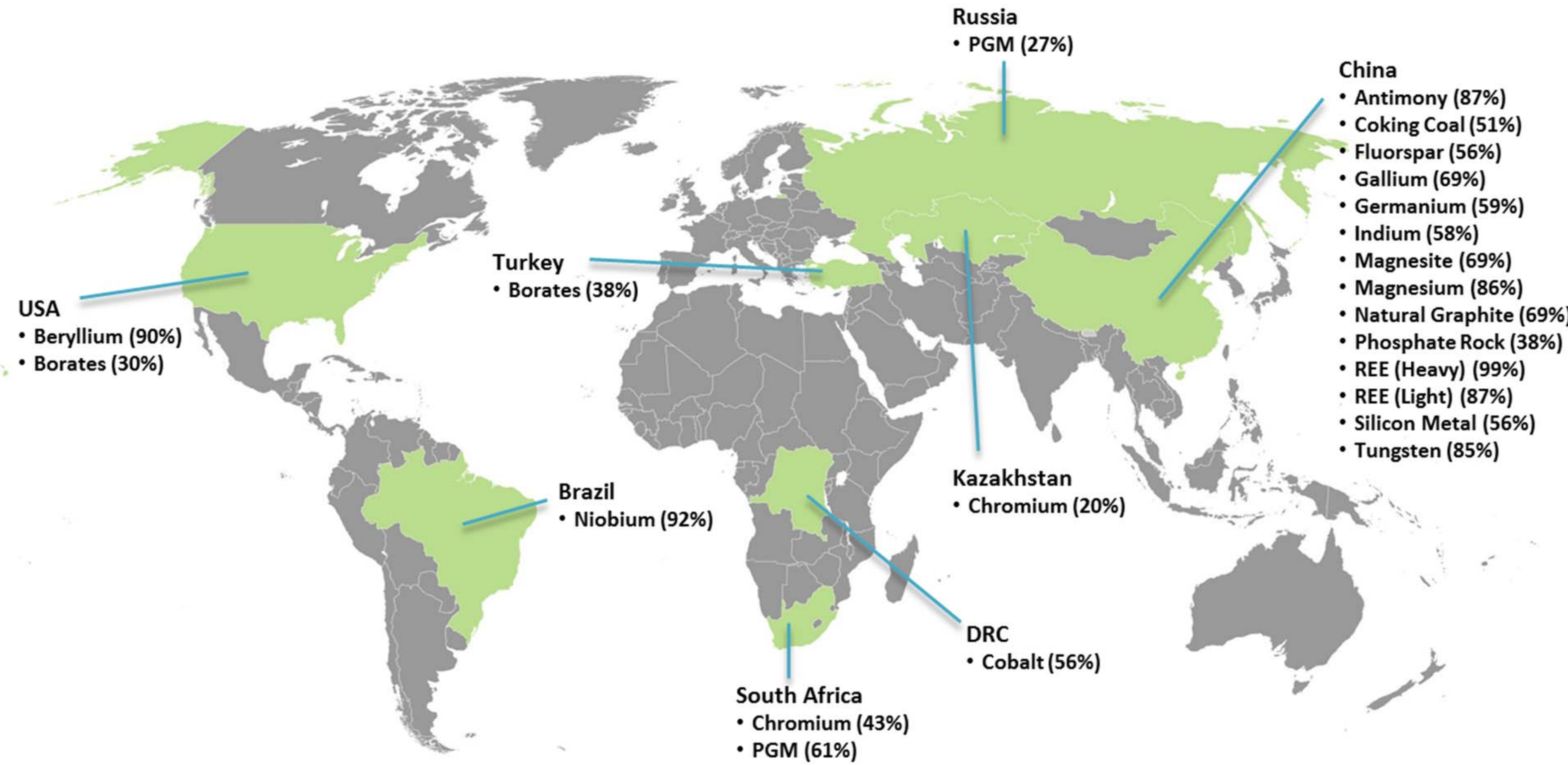
REPORT ON CRITICAL RAW MATERIALS FOR THE EU

Report of the Ad hoc Working Group on defining critical raw materials

May 2014



Antimony	**Beryllium**	**Borates**	**Chromium**	**Cobalt**	**Coking coal**	**Fluorspar**
Gallium	**Germanium**	**Indium**	**Magnesite**	**Magnesium**	**Natural Graphite**	**Niobium**
PGMs	**Phosphate Rock**	**REEs (Heavy)**	**REEs (Light)**	**Silicon Metal**	**Tungsten**	



eit RawMaterials

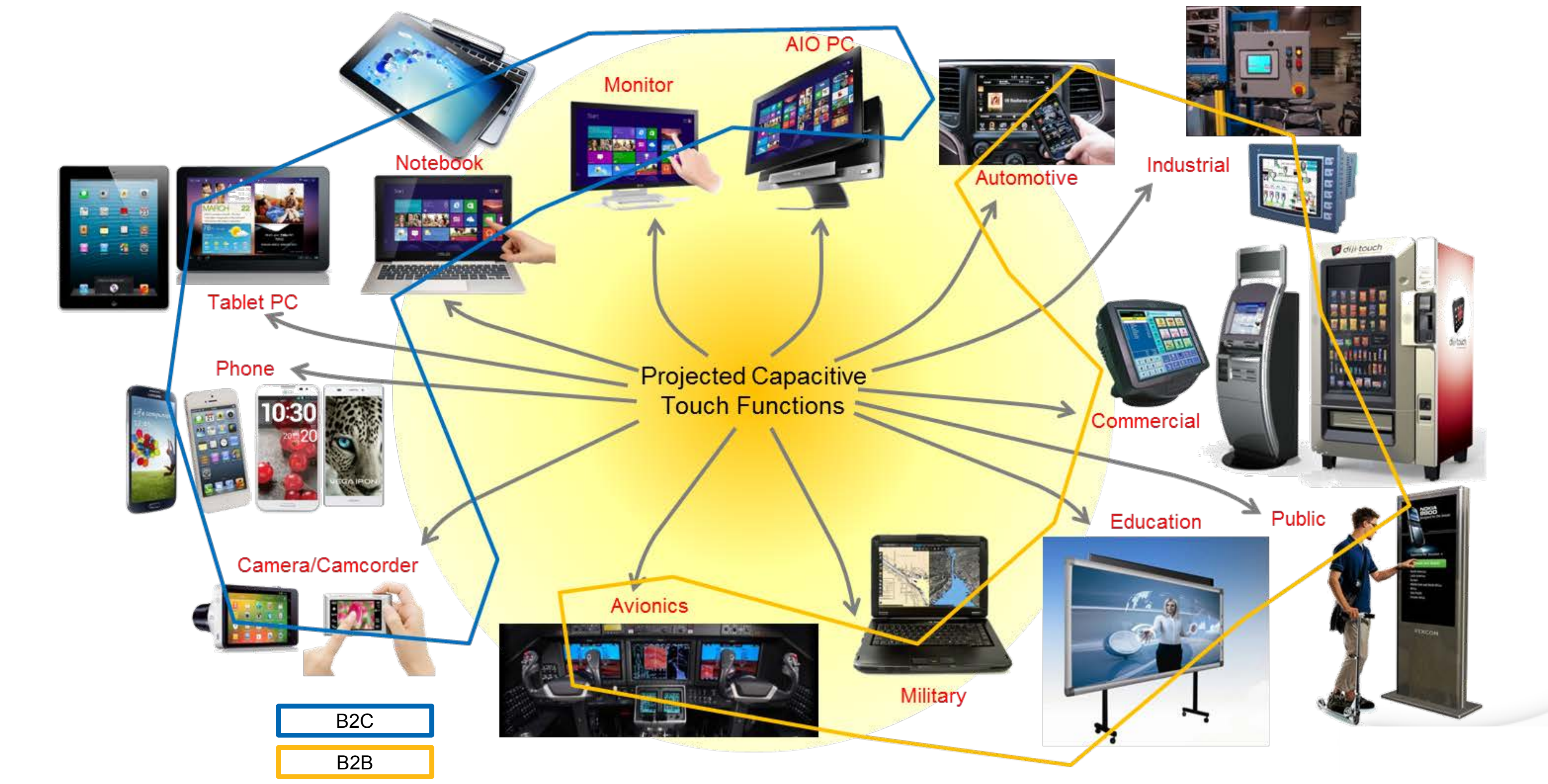
EIT's 2014 Call for KICs Proposals

EIT Raw Materials was designated as an EIT Knowledge and Innovation Community (KIC) by the EIT Governing Board on 09 December 2014. The below provides some information about the challenges the KIC will address in the field of raw materials (sustainable exploration, extraction, processing, recycling and substitution) and the impact it will generate.

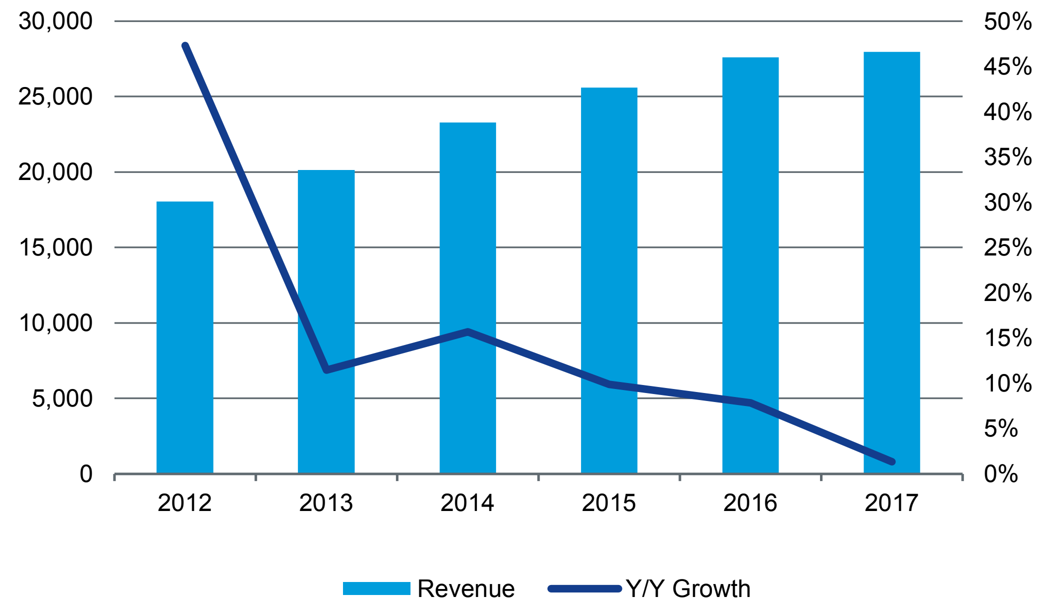
Indium in touch sensors

- Touch technology is increasingly applied to all types of electronic devices used daily.
- With projected capacitive touch sensors being applied as almost a standard to smartphones and other consumer electronics, capacitive touch technology is replacing other technologies used in almost every touch-sensor application.

Touch everywhere



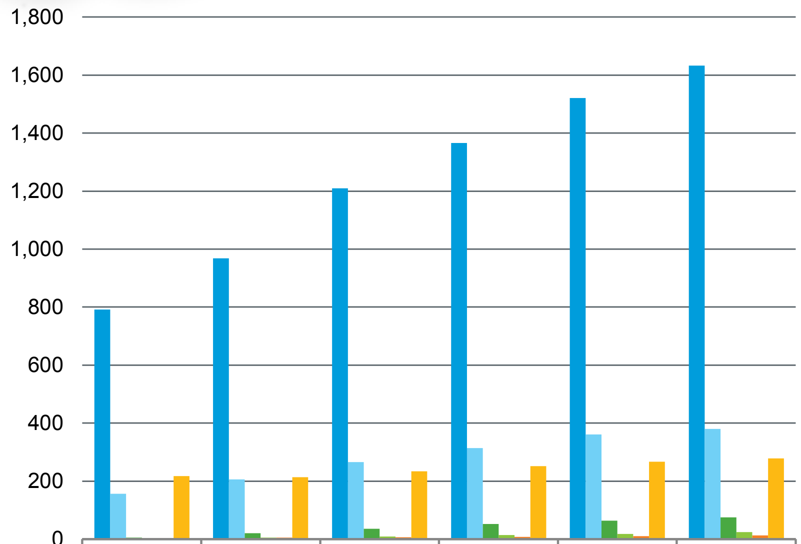
Overall touch panel market forecast ($ million)



Overall touch panel market forecast ($ million)

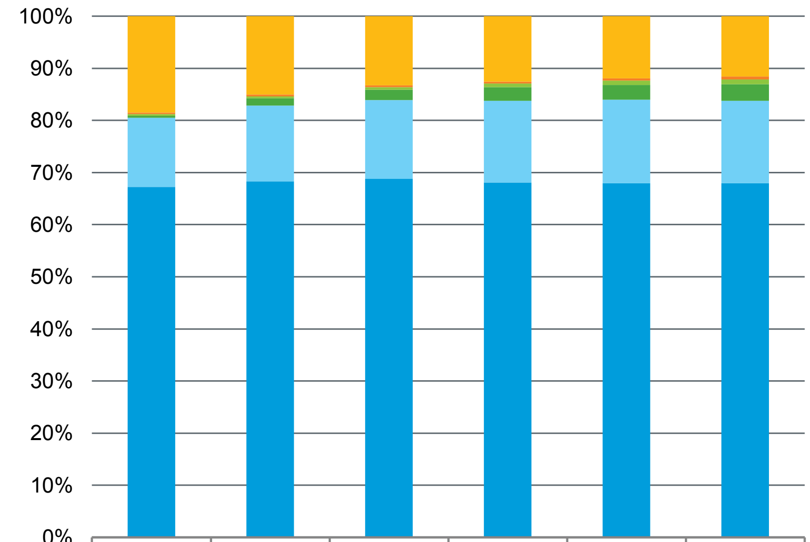
	2012	2013	2014	2015	2016	2017	CAGR
Revenue	**18,054**	**20,125**	**23,282**	**25,586**	**27,591**	**27,960**	**9.1%**
Y/Y Growth	**47.3%**	**11.5%**	**15.7%**	**9.9%**	**7.8%**	**1.3%**	

Touch panel market forecast by major application (Unit: million)



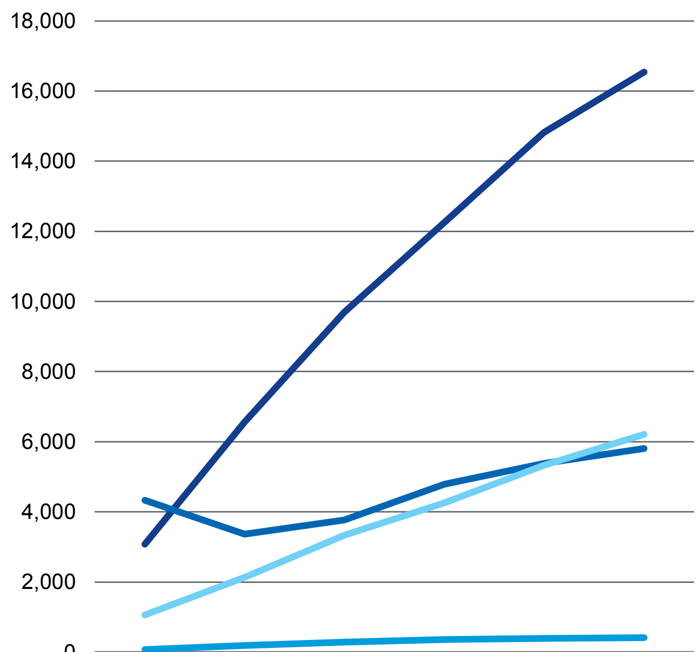
	2012	2013	2014	2015	2016	2017
Mobile Phone	792.0	967.7	1,210.0	1,366.2	1,521.2	1,632.4
Tablet PC	156.0	205.5	265.6	314.4	360.4	380.0
Notebook PC	4.6	20.3	35.2	51.5	63.0	75.3
LCD Monitor	4.2	5.0	8.4	14.1	17.9	23.6
AIO PC	3.7	4.6	6.3	7.9	10.4	12.2
Others	217.6	213.3	233.5	251.7	266.9	278.8

Touch panel market share by major application (%)



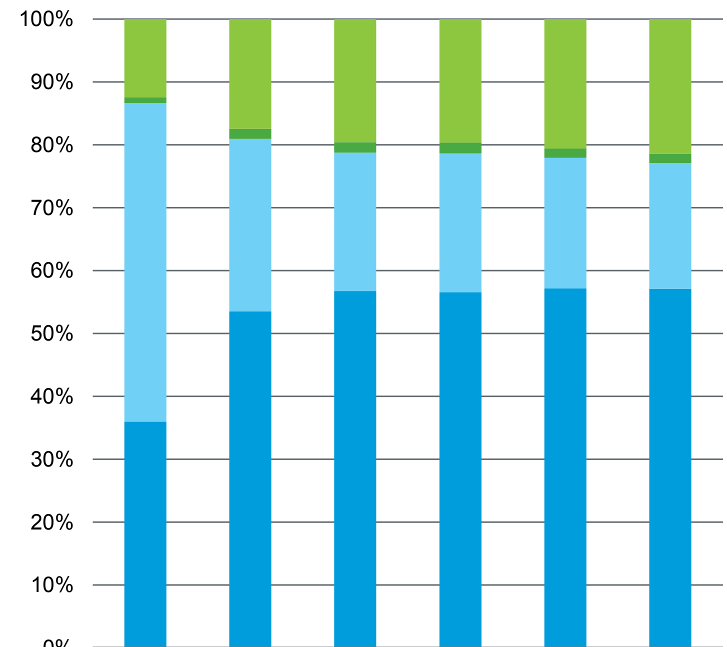
	2012	2013	2014	2015	2016	2017
Others	18%	15%	13%	13%	12%	12%
AIO PC	0%	0%	0%	0%	0%	1%
LCD Monitor	0%	0%	0%	1%	1%	1%
Notebook PC	0%	1%	2%	3%	3%	3%
Tablet PC	13%	15%	15%	16%	16%	16%
Mobile Phone	67%	68%	69%	68%	68%	68%

Capacitive touch panel market forecast by layer structure (Ksqm)



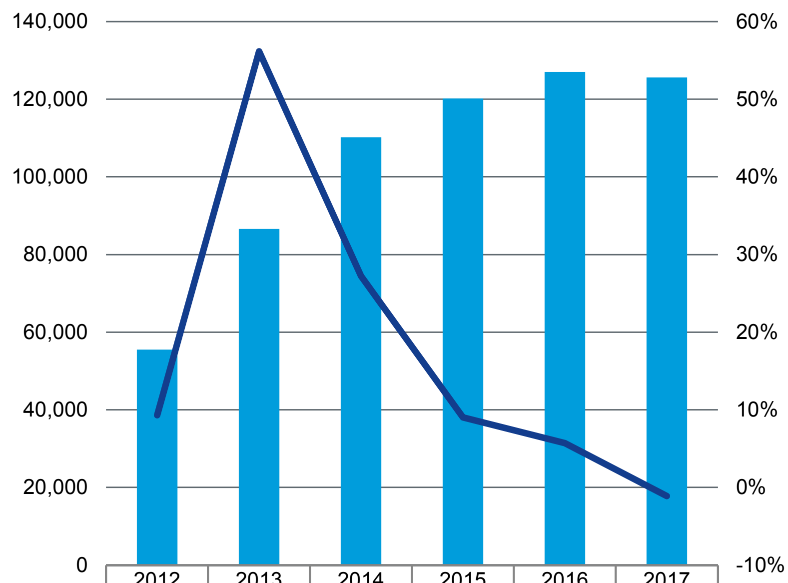
	2012	2013	2014	2015	2016	2017
Film Sensor	3,079	6,561	9,690	12,247	14,821	16,543
Glass Sensor	4,331	3,366	3,764	4,786	5,380	5,808
Hybrid Sensor	77	191	281	364	389	417
Embedded Sensor	1,062	2,139	3,338	4,252	5,333	6,205

Capacitive touch panel market forecast by layer structure (%)



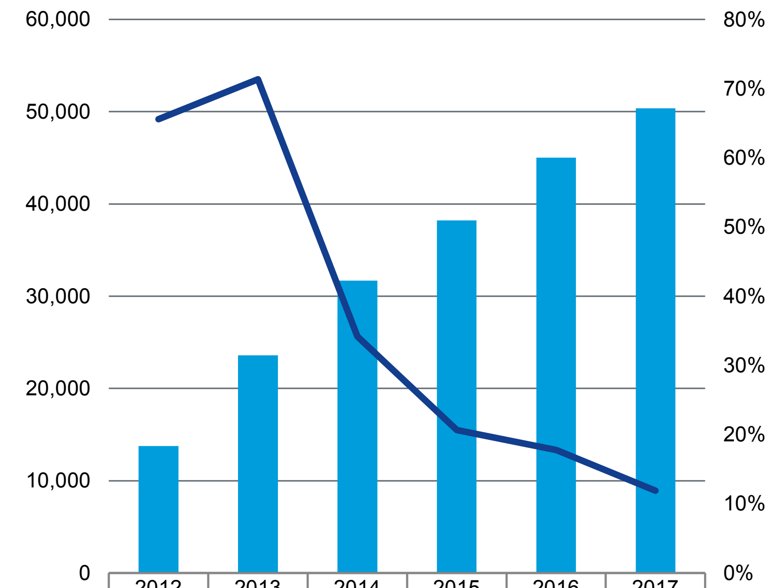
	2012	2013	2014	2015	2016	2017
Embedded Sensor	12%	17%	20%	20%	21%	21%
Hybrid Sensor	1%	2%	2%	2%	2%	1%
Glss Sensor	51%	27%	22%	22%	21%	20%
Film Sensor	36%	54%	57%	57%	57%	57%

Overall transparent conductive film market forecast (¥ million)



	2012	2013	2014	2015	2016	2017
Revenue	55,482	86,632	110,226	120,162	126,999	125,580
Y/Y Growth	9.3%	56.1%	27.2%	9.0%	5.7%	-1.1%

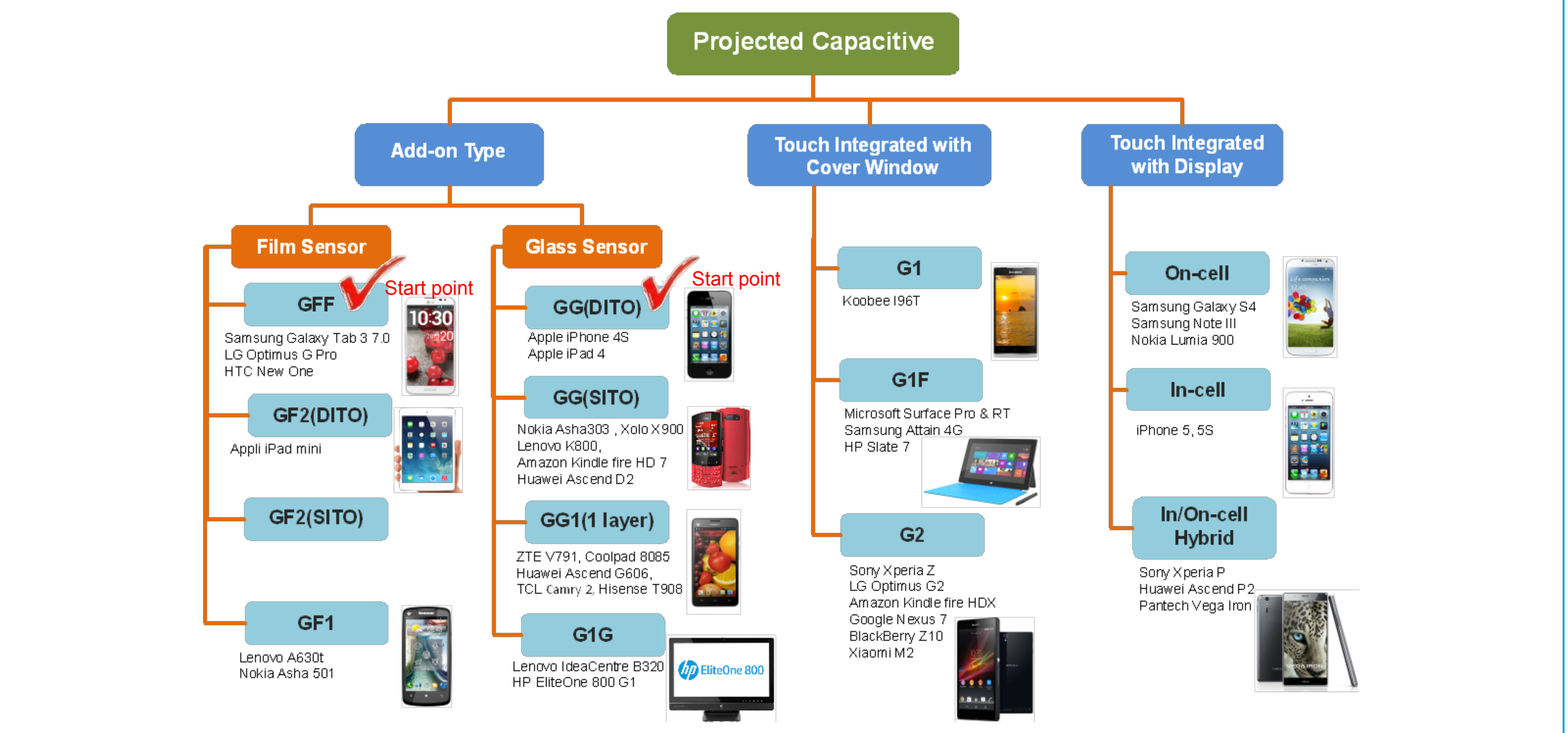
Overall transparent conductive film market forecast (Ksqm)



	2012	2013	2014	2015	2016	2017
Area	13,775	23,605	31,673	38,224	45,018	50,383
Y/Y Growth	65.6%	71.4%	34.2%	20.7%	17.8%	11.9%

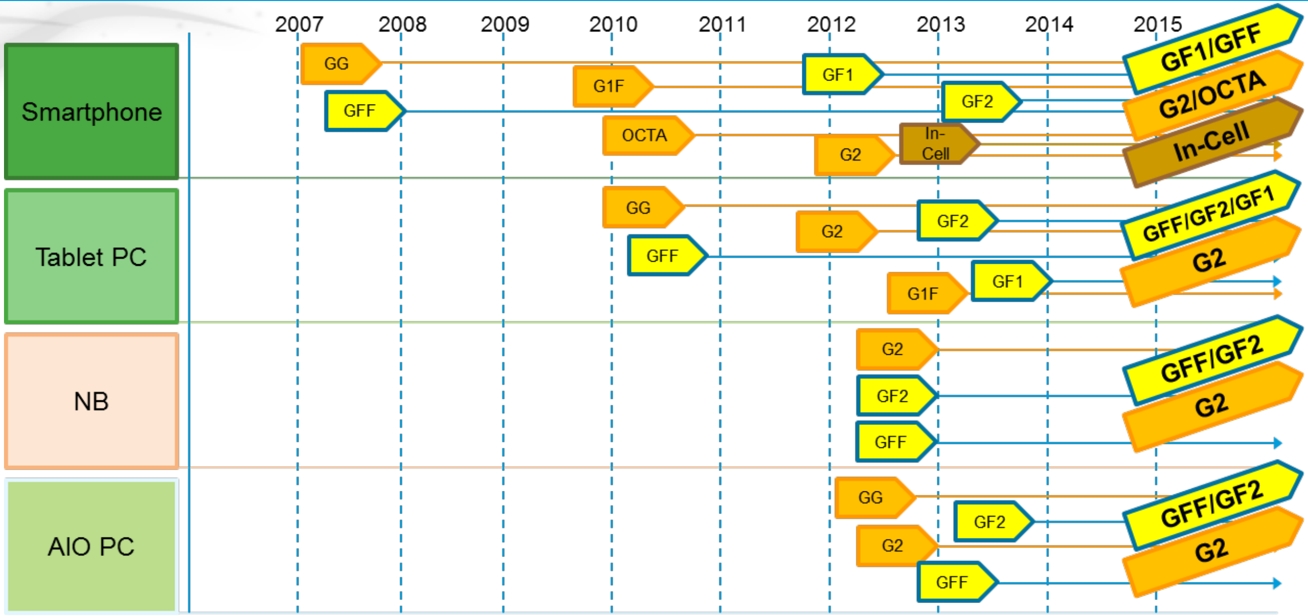
- The market initially started with glass types (GG, DITO) and film types (GFF), but currently there are more than 10 types of touch panels with different layer structures.
- Each method has its pros and cons according to the technology, production cost, client preference, and each developer's situation.

Projected capacitive touch layer types and major products of each type

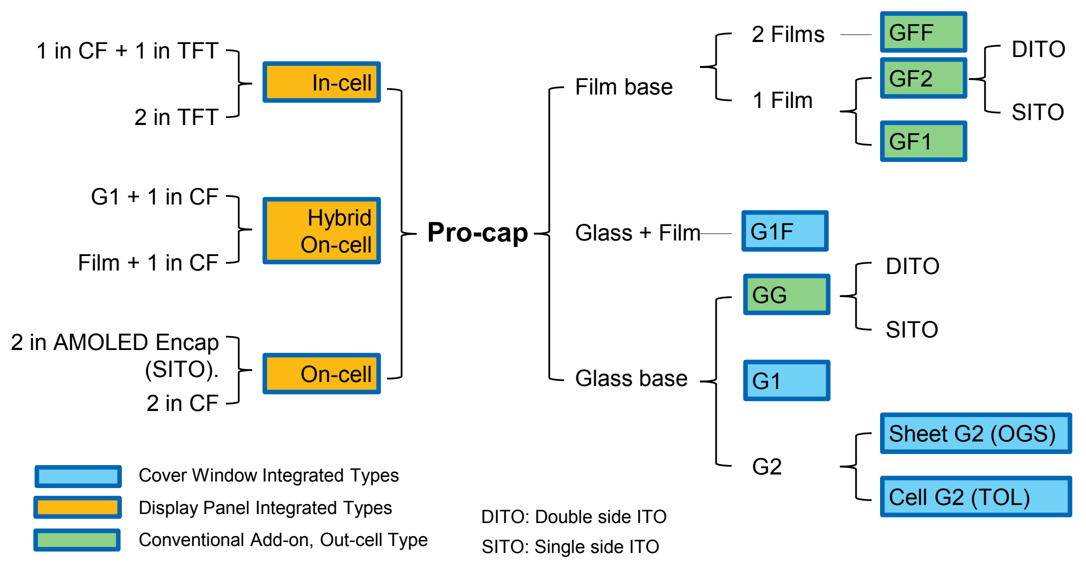


GG - cover glass+ ITO glass sensor
GFF - cover glass + two ITO film sensors

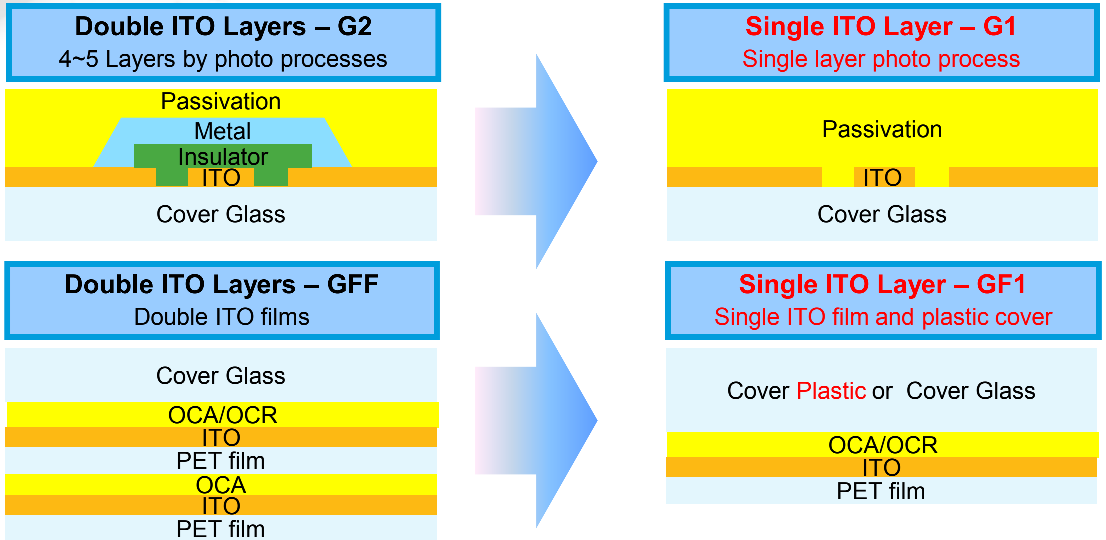
History and forecast: Projected capacitive layers by application



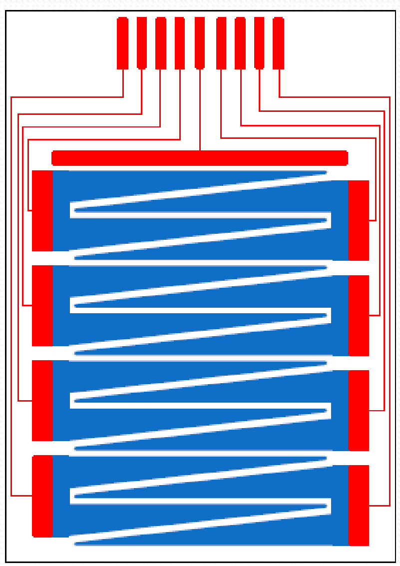
Projected capacitive touch type by layer structure



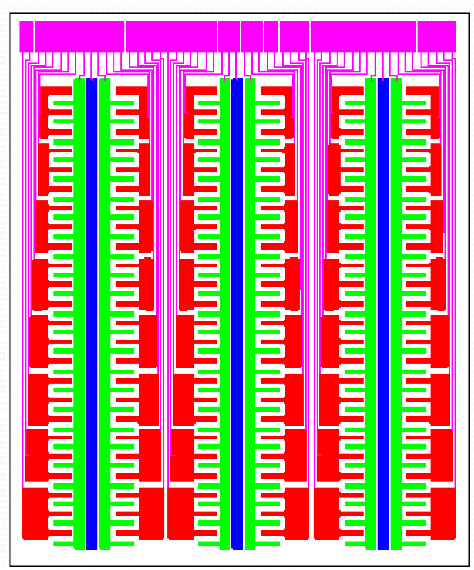
Advantages of one layer type solution over two layer type: Simpler process and lower cost



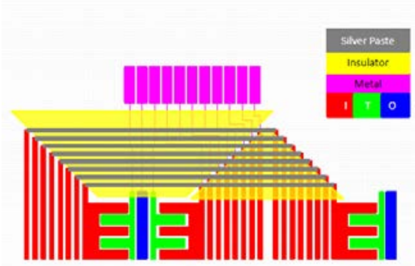
Single layer touch patterns (Without a via hole and with a via hole)



Single point + Gesture

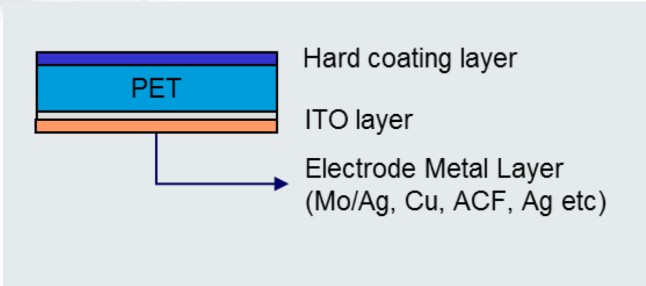


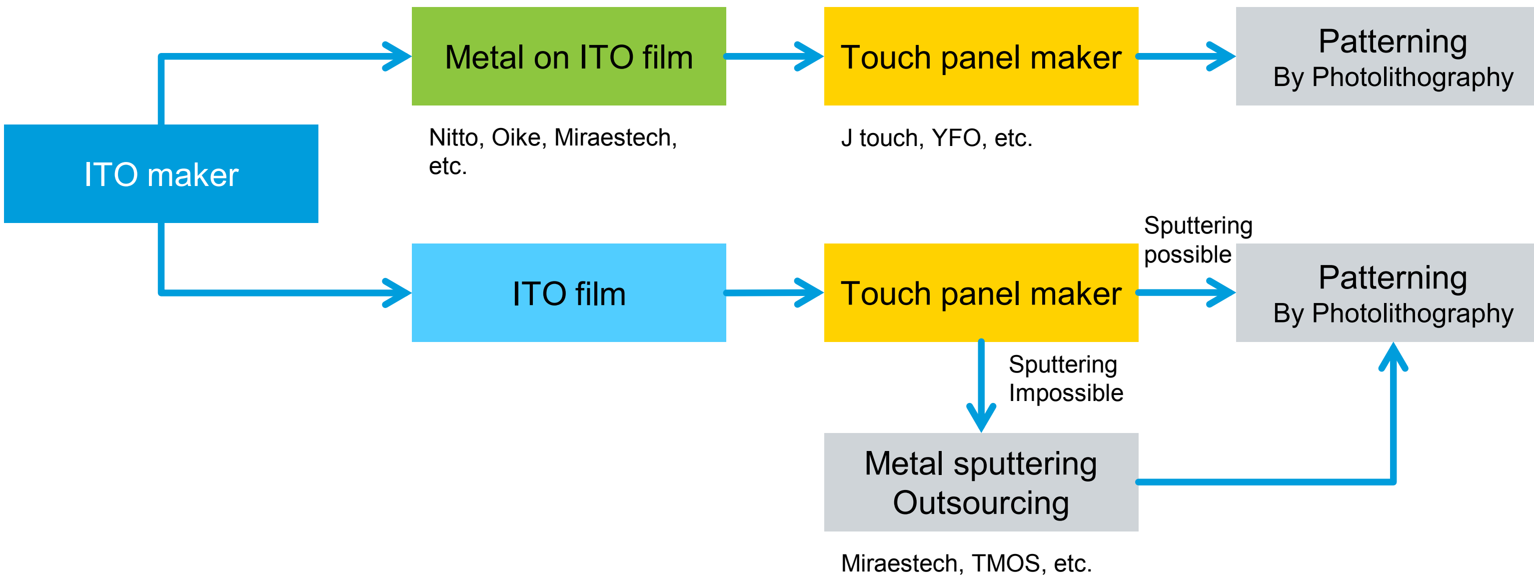
Single Layer with Multi-touch
(w/o a via hole)



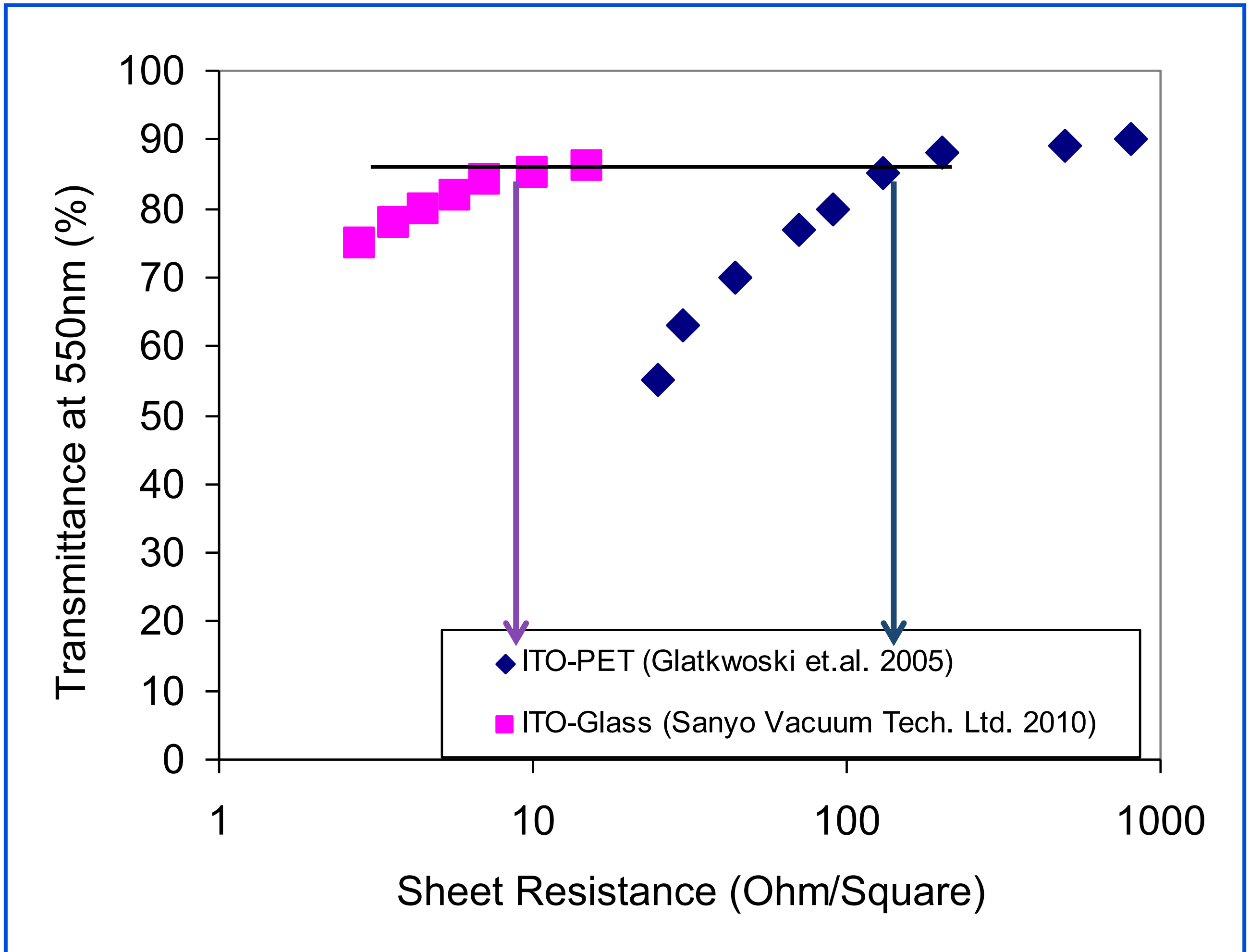
Single Layer with Multi-touch
(with a via hole)

Structure and value chain of metal on ITO





ITO-on-glass (fragile) and ITO-on-PET (a bit pendable) transmittance vs. sheet resistance - NOT flexible and vacuum-processed
REFLECTION and HAZE IMPORTANT ISSUES, not only sheet resistance



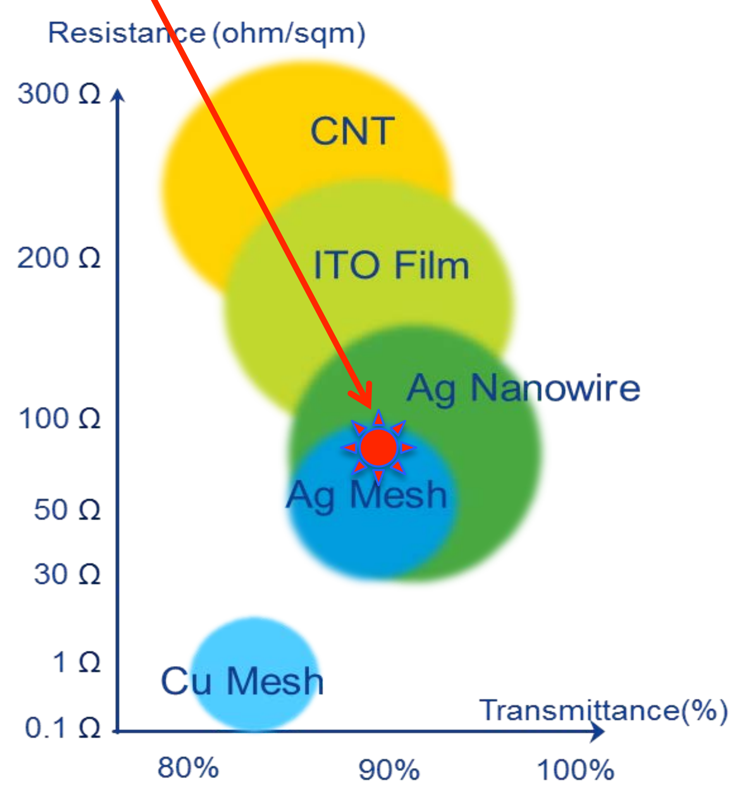
Capacitive Touch sensor stack with ITO – 2 ITO layers + ***14 other layers***

Cover Window
OCA
AR1
AR2
ITO
IM1
IM2
PET
OCA
AR1
AR2
ITO
IM1
IM2
PET
Color matching
AR3
LCD

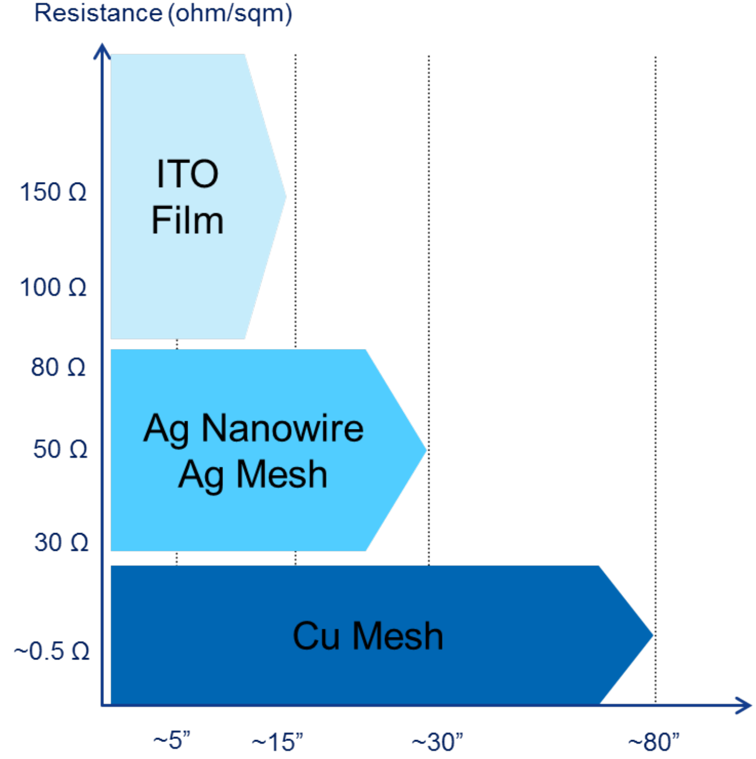
Emerging materials: metal mesh and nanowires, conducting polymers, CNT, graphene

Aalto Univ./ Canatu CNT film: below 100 ohm/sq @ 90 % T

Transparent conductive film comparison: Resistance and transmittance



Transparent conductive film comparison: Resistance and screen size



Metal-based transparent conductive film types – Overall

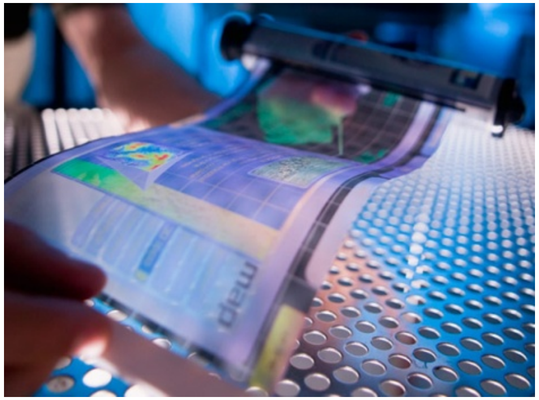
	Ag Nanowire	Ag Halide	Cu Mesh	Ag (Direct Printing)	ITO
Resistance(Ω)	30~50Ω	60Ω	0.1~0.5Ω	60Ω	80Ω or higher
Transmittance(%)	More than 90%	89% ~ 91%	≈ 85%	More than 90%	89% (Based on 150Ω)
Merit	Able to use existing touch panel production lines	Micro patterning Double side patterning	Strong against static electricity Able to use existing PDP mesh infrastructure	Bezel wiring can be formed at once	Superior pattern visibility Proven for mass production Secured ample capacity
Demerit	Limited makers, milky color, weak chemical resistance	Moiré Limited width in production lines	Moiré, corrosion	Moiré, haze	Instability in indium supply
Flexibility	Good	Good	Good	Good	Bad
Method of securing pattern visibility	Partial etching, half etching	Partial etching, half etching	Introduce blackened layer	Process separate layer that controls light reflection	Introduce index matching layer
Layer Type	GFF / GF	GF2	GFF / GF	GFF / GF	GFF / GF / GF2
Price (ITO sensor: 1)	x1.2	x0.8~1	x0.8~1	x1	x1
Target Application	Large laptop~AIO PC	Smartphone~AIO PC	Large laptop~electronic board	Large laptop~AIO PC	Smartphone~laptop
Major Supplier	LGE, E&H, Toray, Okura, Nitto, Hyosung, Cheil Industry, Iljin Display, O-film, Carestream	Fujifilm, Mitsubishi Paper, Kodak	LG Chem, Toppan, DNP, Toray, Atmel, Panasonic, Fujikura	Mirae Nanotech, O-film, LGI	Nitto, LG Chem, Oike, Sekisui, Gunze, MAX film, LG Hausys, Miraestech, O-film

Requirements to material and devices for flexible, transparent and stretchable electronics

Silicon and ITO : Hard, Fragile → Plastic: Flexible, Elastic

Fabrication on plastic substrate

→ **Low temperature process**



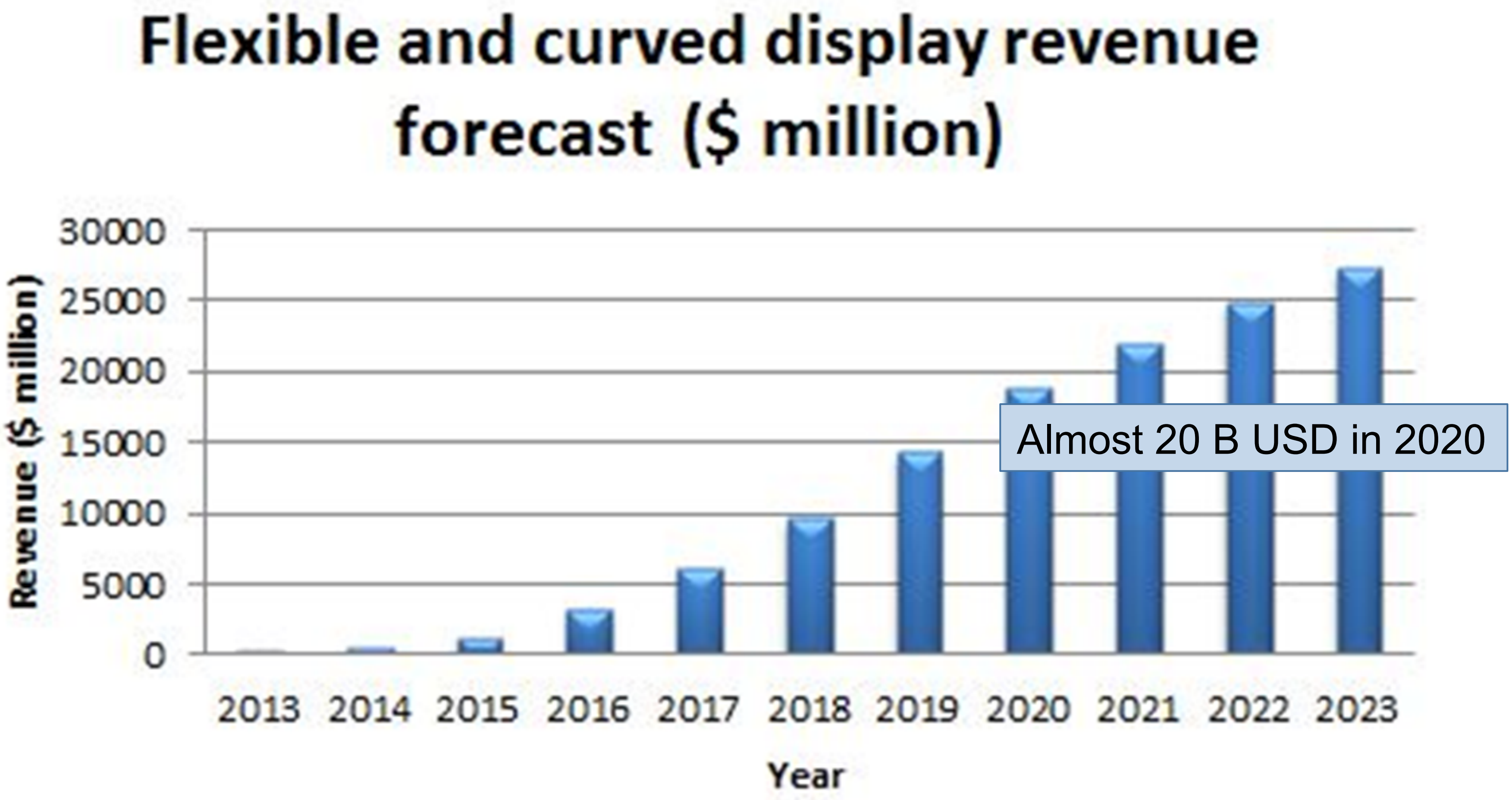
Hewlett-Packard

Low-cost fabrication

→ **Atmospheric pressure process**
High-speed printing method
Roll-to-roll manufacturization

Deflection in the market 1:

Flexible Products Finally Coming of Age



Source: Touch Display Research, Flexible and Curved Display Technologies and Market Forecast Report, September 2013

Deflection in the market 2:
ITO Replacements Finally Coming of Age

- Touch Display Research forecasts the non-ITO transparent conductor market will grow from $206 million in 2013 to $8 billion by 2021.

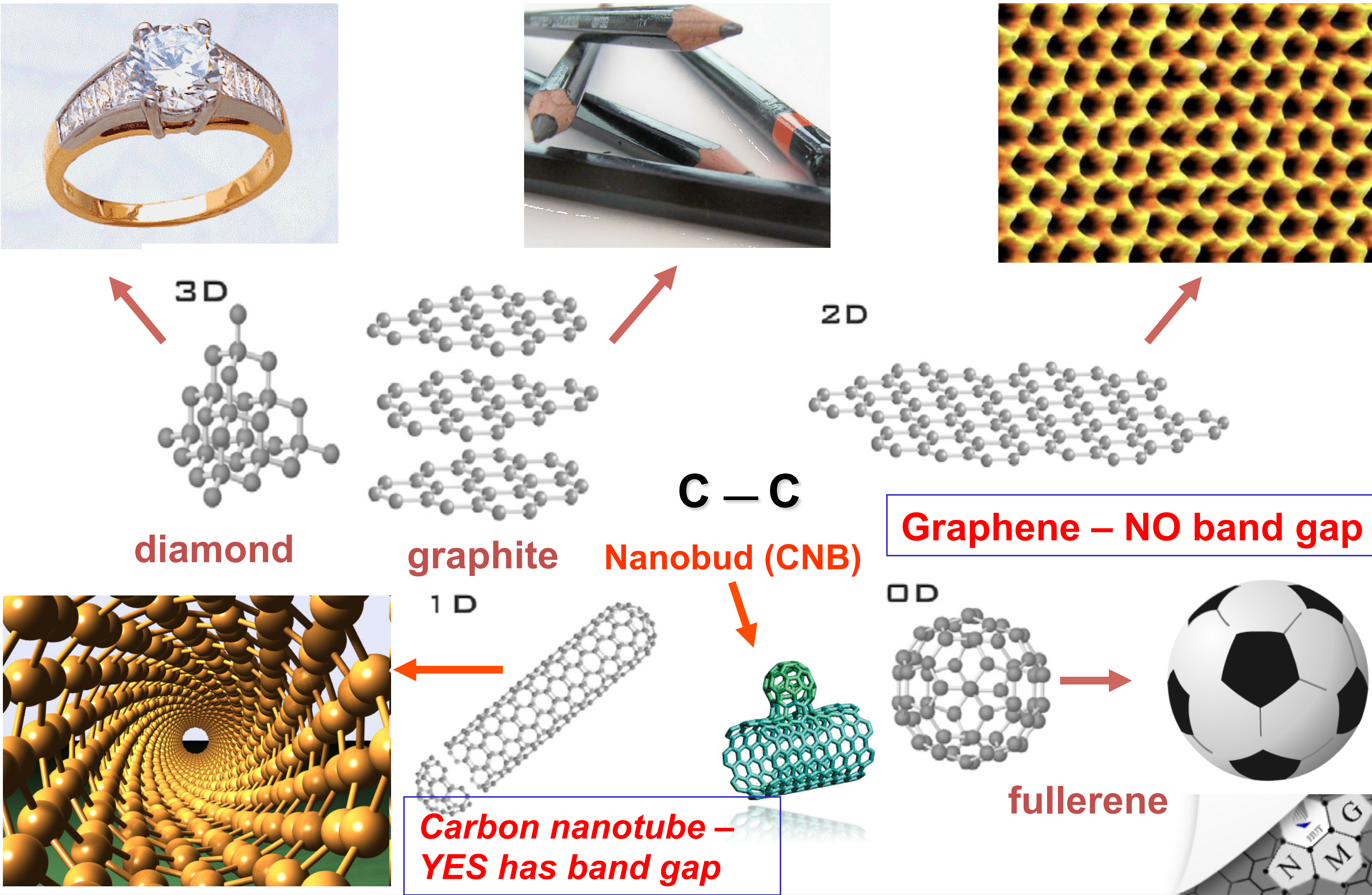
Source: Touch Display Research, ITO-replacement report, Nov, 2014

Traditional thin film transistors materials

Material	Mobility (cm^2/Vs)	Method (Process temp.)	Flexibility	Large area	Cost	Stability
Poly-Si	30~300	Vac. CVD (500°C)	Bad	Fair	High	Very good
Amorphous-Si	0.5~1	Vac. CVD (> 200°C)	Bad	Fair	High	Very good
Oxide (InGaZnO)	1~10	Vac. Sputter (R.T.~200°C)	Good	Fair	Moderate	Very good
Organic	0.01~10	Solution, Sublimation (R.T.)	Good	Very good	Low	Bad

Additional important parameter: on/off ratio is larger than 1 000 000 = 10^6
(needed for display and digital (IC) applications)
Manufacturing yield very important for real applications

Allotropes of carbon – CNT and graphene - NOVEL NANOCARBONs for electronics ?



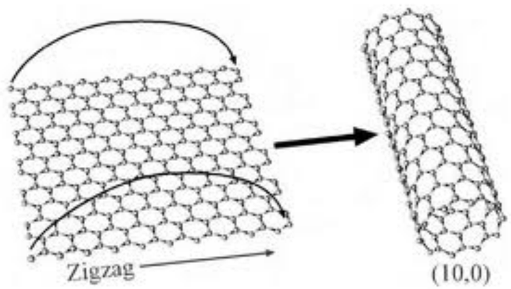
SWCNT and graphene show extremely high carrier mobility for flexible electronics applications = **fast large devices ->** ***Ideal material for printed electronics ?***

Material	Mobility (cm^2/Vs)	On/off ratio	Manuf. method (Process temp.)	Flexibility	Cost	Stability
Individual SWCNT on the subtrate	10 000 – 200 000	**10^8**	CVD (600-900°C)	Very good	**High**	Very good
SWCNT thin film on the subtrate	5 - 2000	**10^4 - 10^8**	Depositon from solution or gas phase (ambient)	Very good	**Low**	Very good
Free-standing graphene single crystal	100 000 - 1 000 000	**2-100**	Exfoliation (not an industrial manufacturing process)	Very good	**Very High**	Very good
Graphene thin film on the Si subtrate	1 000 – 5 000	**2-100**	CVD (900-1050°C)	Very good	**High**	Very good

On/off ratio: For digital electronics and display backplane $>10^6$

New 2-D materials –lower mobility, on-off OK, high cost

SWNT challenge is the material control: not only (n,m), but also *bundling, length, orientation*



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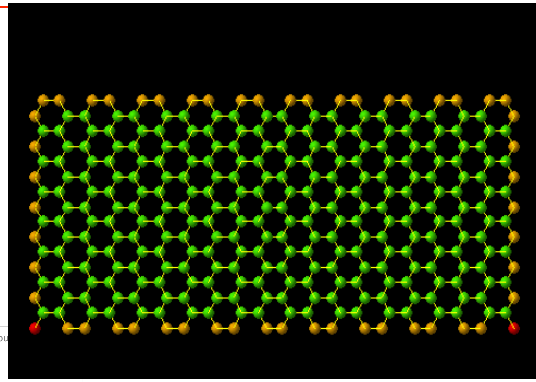
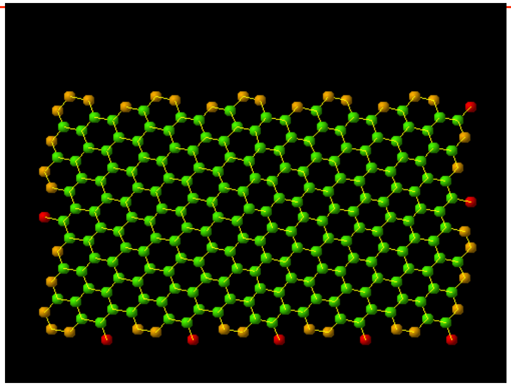
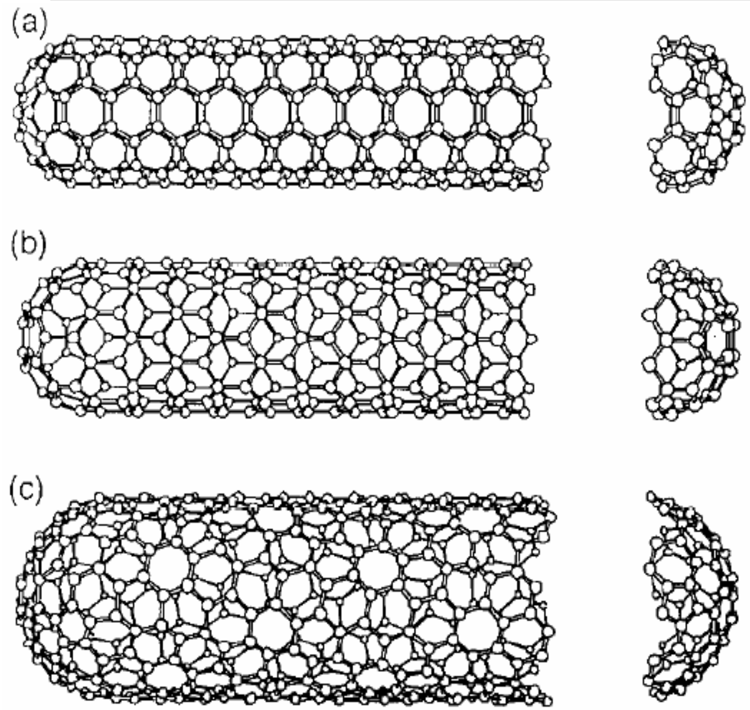
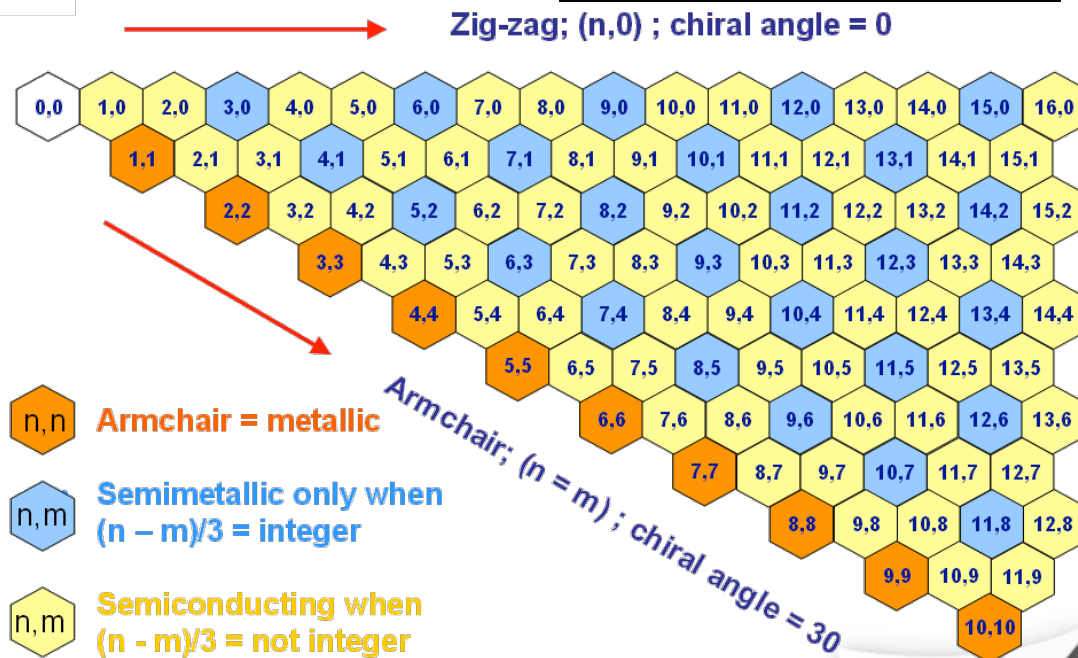
and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.



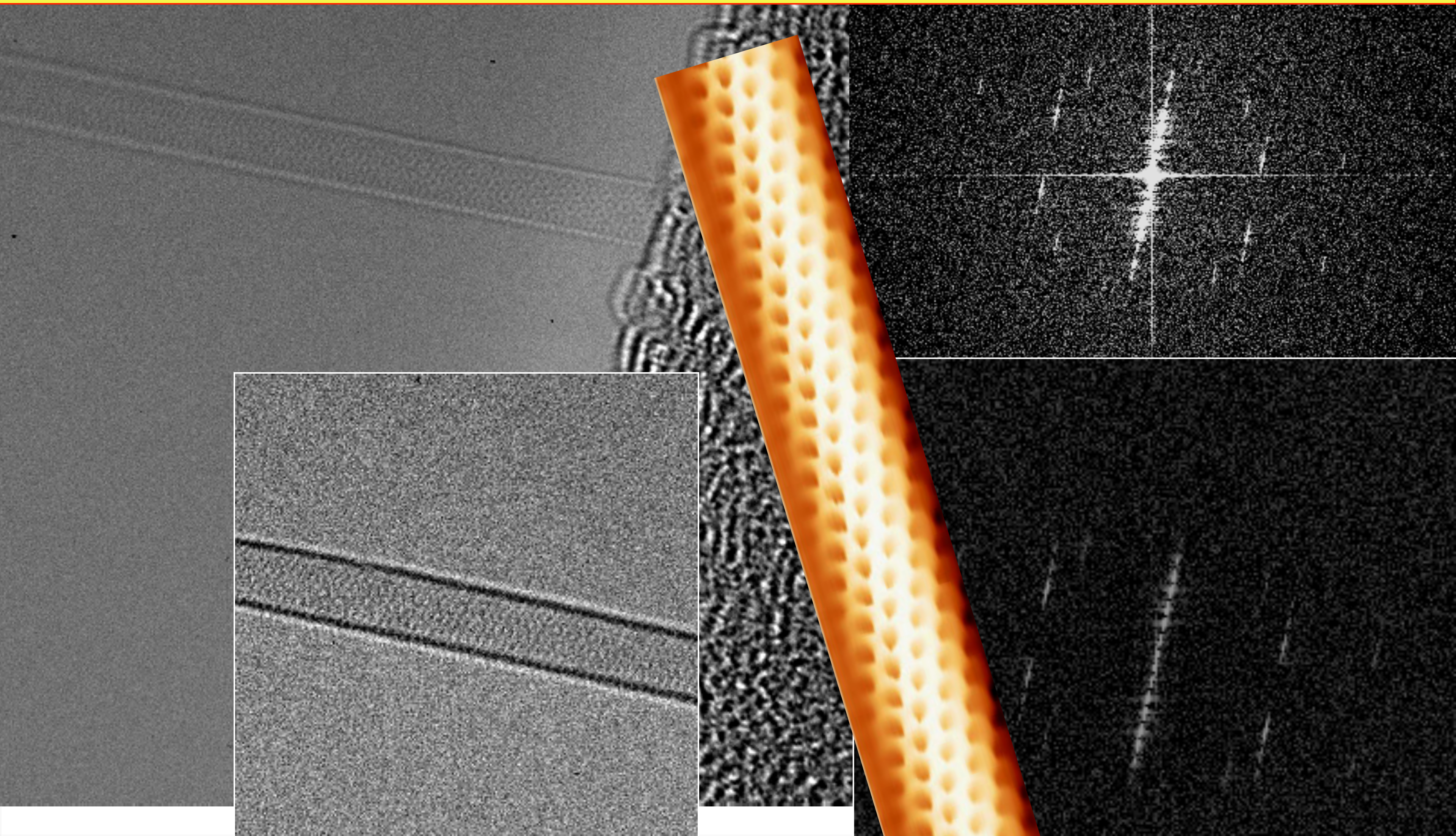




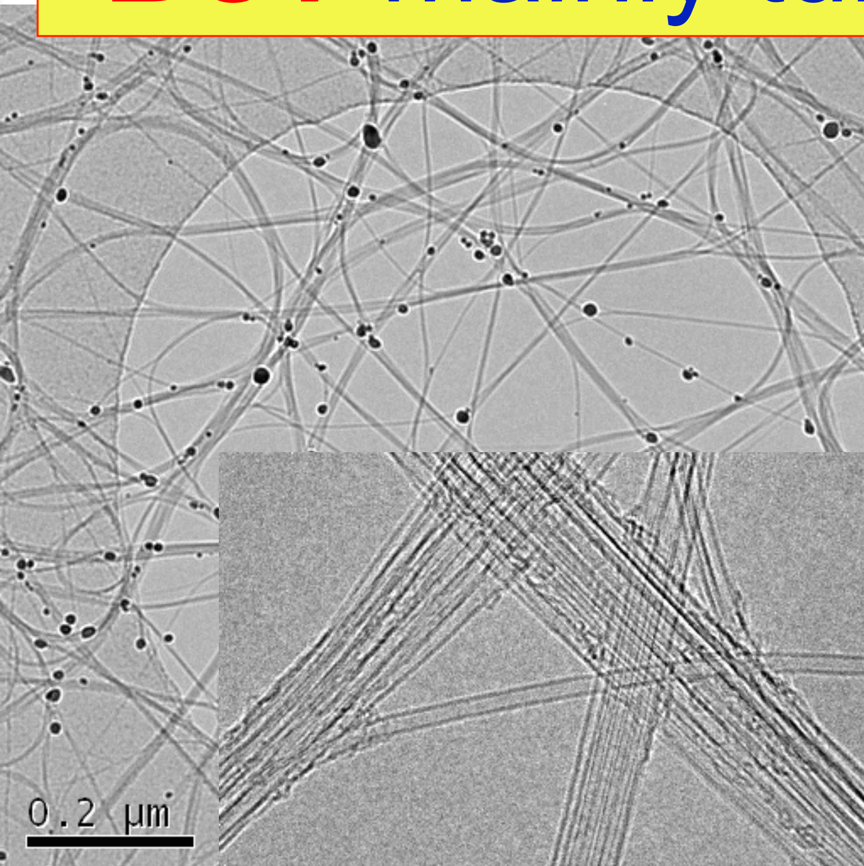


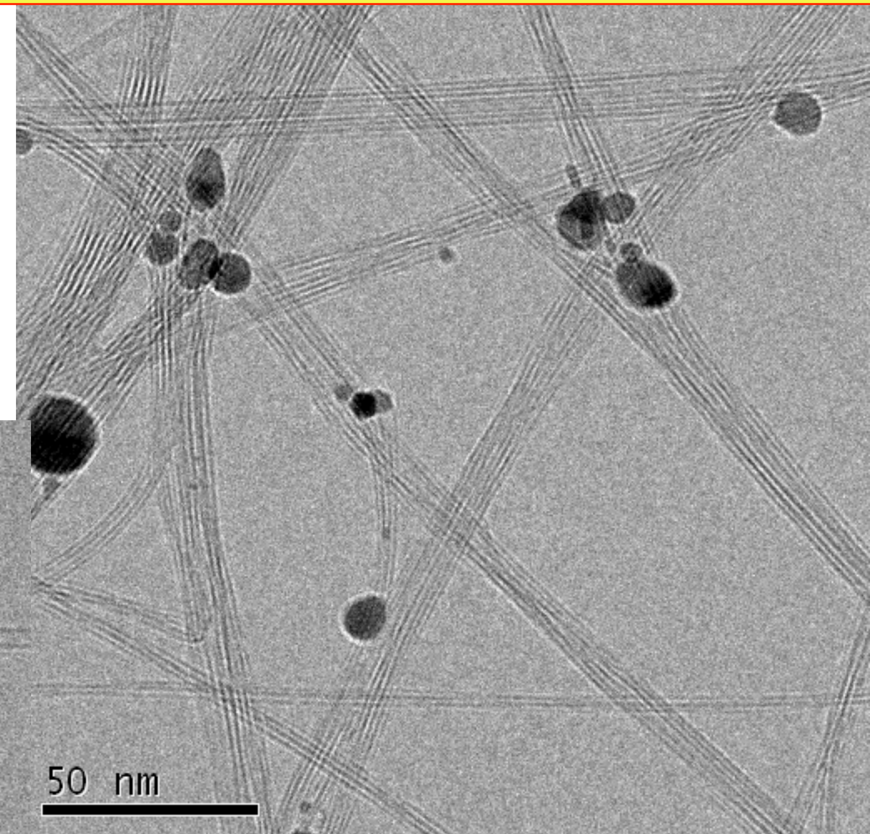
Rolling in different directions makes different kinds of tubes

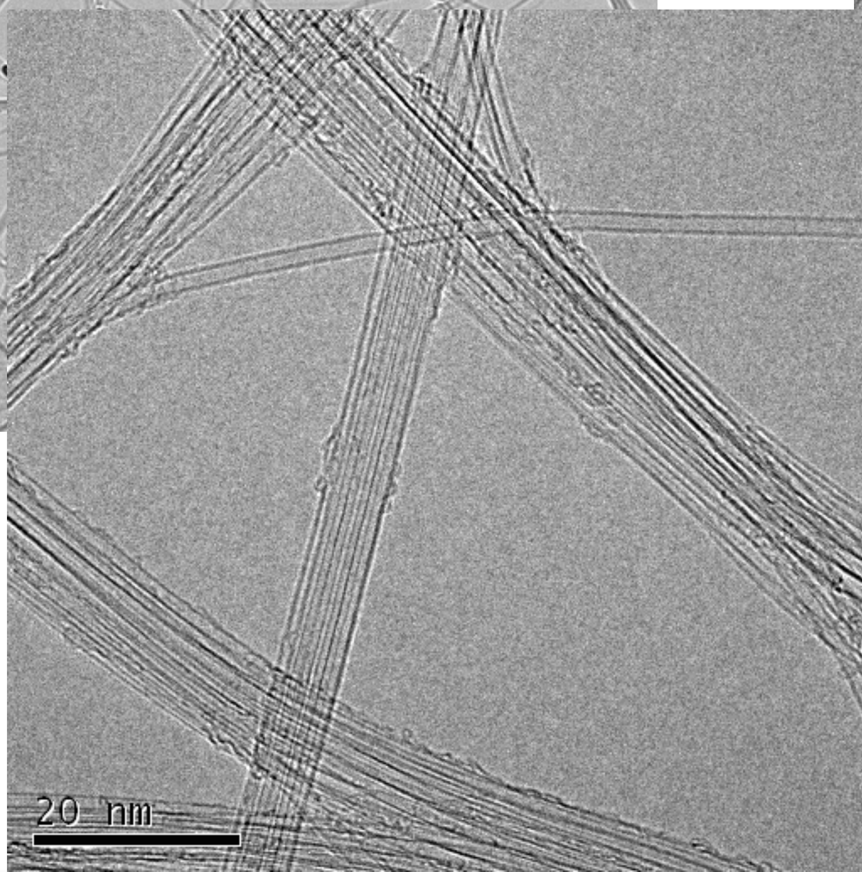
We like to show ***individual tubes***



BUT mainly tubes are ***in bundles***







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- **Main results** for TCF, TFTs and solar cells
- **Future plans** – how to use the results

GOALS

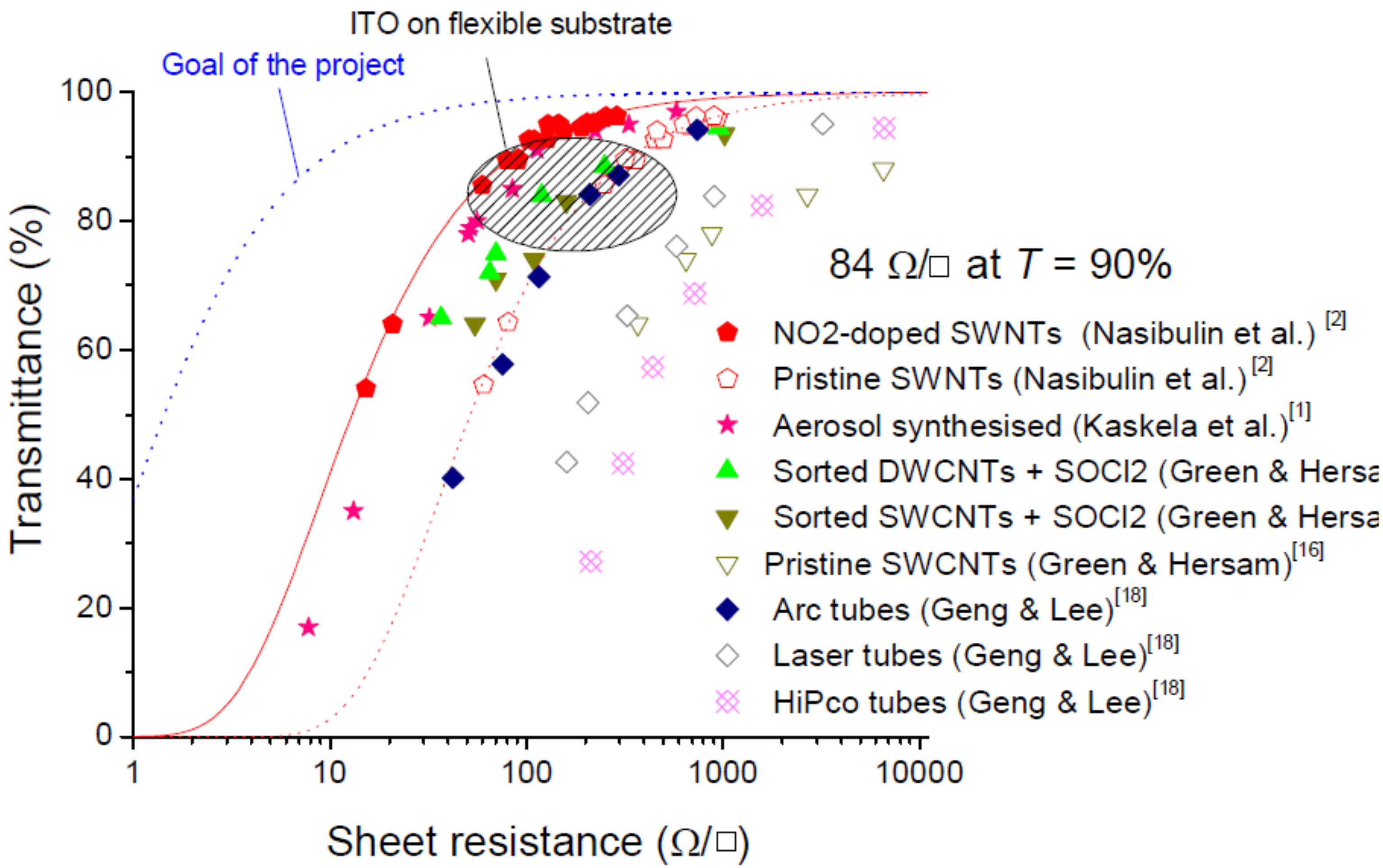

Fig. 3. Comparison of different transparent electrode materials: sheet resistance versus optical transmittance at 550 nm. The data produced by Aalto are shown by open and solid pentagons; the red lines show theoretical fits to our data; the blue line is for ITO on glass and the goal of the project.

GOALS

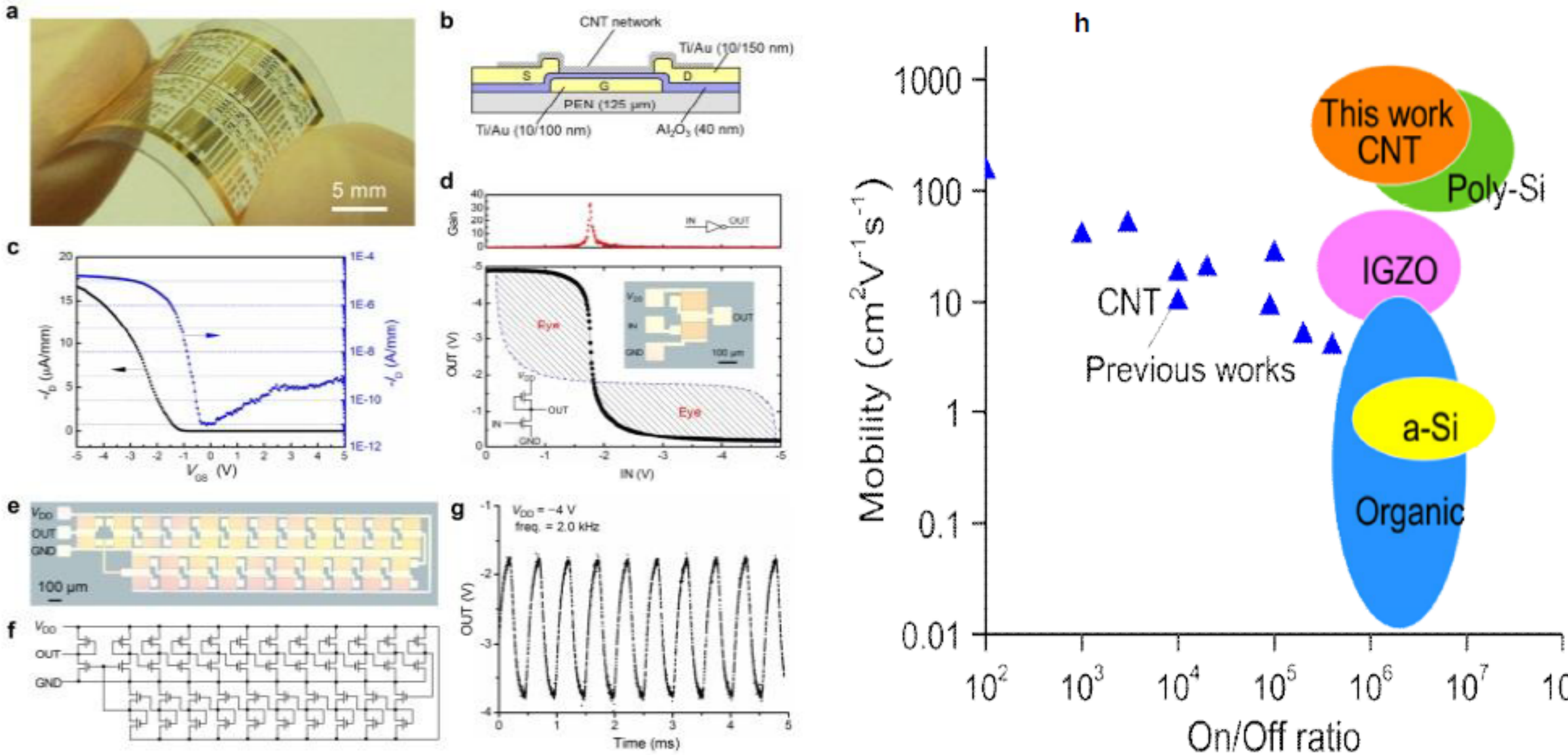

Fig. 4. SWCNT TFTs and ICs on flexible substrate. **a)** Photograph of fabricated devices on a flexible and transparent PEN substrate. **b)** Schematic cross section of a bottom gate TFT on PEN substrate with Al_2O_3 gate insulator. **c)** Transfer characteristics of a typical TFT with L_c=100 μm at V_{DS}=-0.5 V, W_c=100 μm. **d)** Input-output and gain characteristics of an inverter. Insets show the optical micrograph, circuit diagram and symbol of the inverter. **e, f)** Optical micrograph and circuit diagram of a 21-stage ring oscillator. **g)** Output characteristics of the ring oscillator with oscillation frequency of 2.0 kHz at V_{DD}=-4 V. **h)** Mobility and on/off ratio. Comparison between our SWCNT TFTs with other representative TFTs based on SWCNT network[6], amorphous-Si, polycrystalline Si, In–Ga–Zn–O semiconductors, and organic materials.

Provide Technology for Future Flexible, Bendable and Stretchable Devices

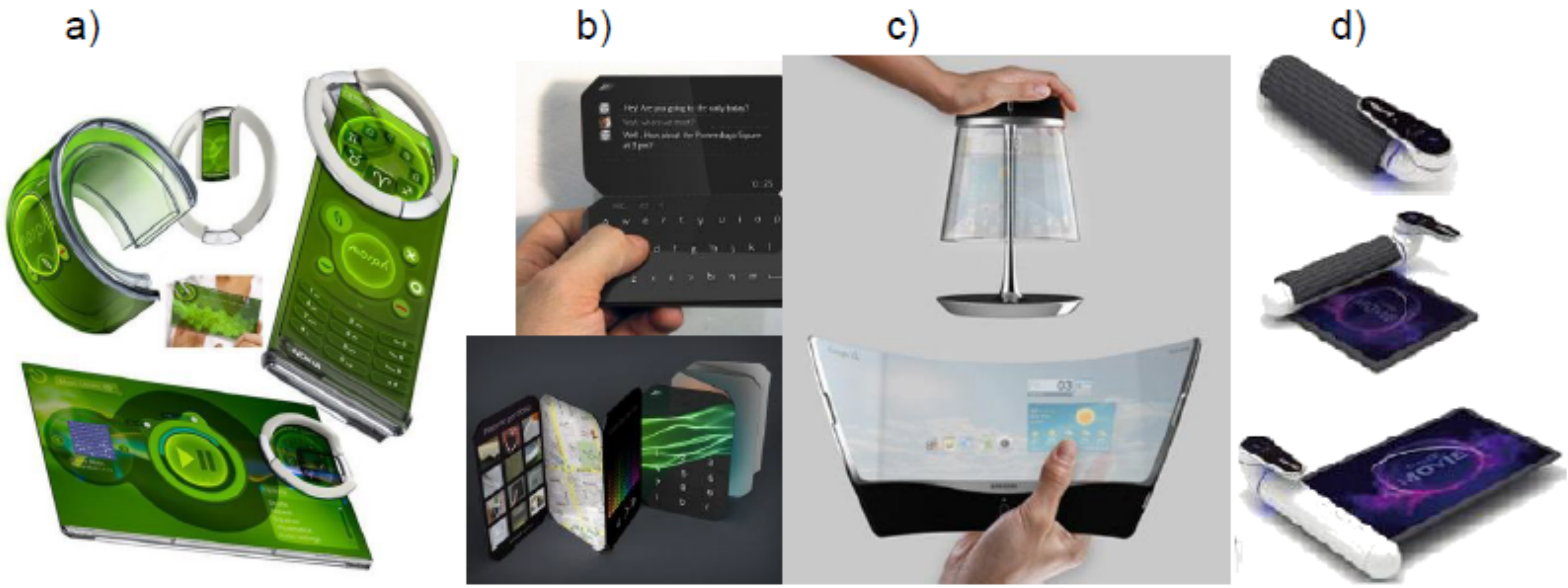

Fig. 1. A few examples of future concepts based on transparent, flexible and conductive materials: a) Nokia concept Morph; b) Smartphone Booklet Device; c) Curved Tablet Design - a flexible smartphone; d) Pen-sized rollup display. http://www.concept-phones.com/?s=flexible

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Co-funded by the European Union

IRENA
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Japan Science and Technology Agency

http://www.nt15.jp/

ONERA

東京大学
THE UNIVERSITY OF TOKYO

Aix-Marseille université

Aalto University

CNRS

Technical University of Denmark DTU

Nagoya University

WP 1: **Synthesis**

Substrate CVD

S. Maruyama

Aerosol CVD

E. Kauppinen

WP 2: **Formation mechanism**

TEM observation

J. Wagner

Computational model

C. Bichara

S. Maruyama

WP 3: **SWCNT thin films**

Fabrication

H. Shinohara

Transport mechanism

E. Kauppinen

Nagoya University

Aalto University

WP 4: **Device applications**

Transistors

Y. Ohno

Touch sensors

E. Kauppinen

Nagoya University

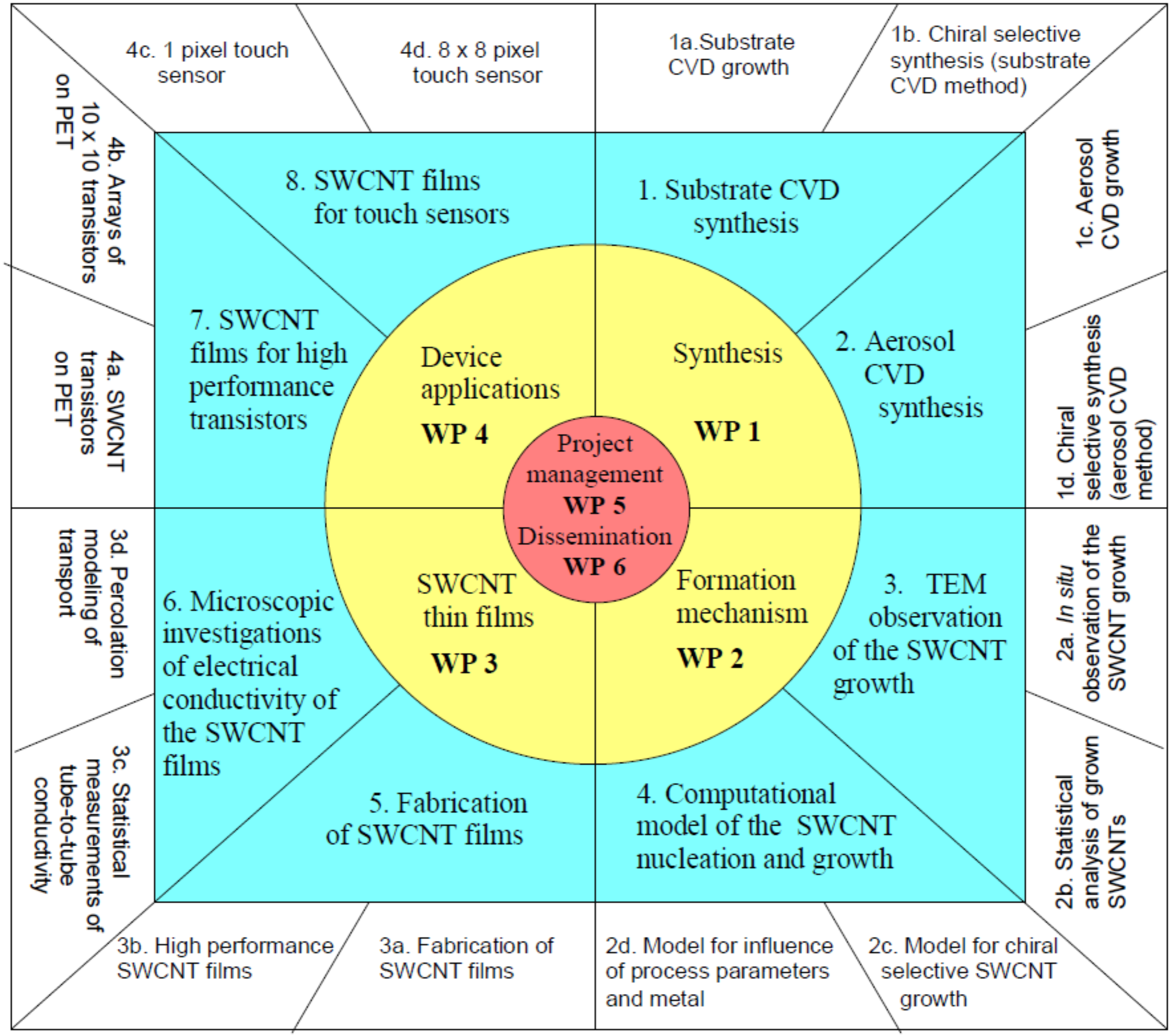


Fig.2. The structure of the project work packaged: 5 Work Packages (in the circle), 8 objectives around the Work Packages, divided into 16 subtasks. Subtasks of WP5 and WP6 are not shown. The illustration includes also the work carried out by the Japanese coordinated project.

Content

- **The need** to replace Indium and Gallium in transparent conductors (TCF) and transistor (TFT): carbon nanotubes as novel materials for flexible, transparent and stretchable electronics ?
- **Project objectives**: meet ITO (indium-tin oxide) and IGZO (indoum-zinc-gallium oxide) specs with flexible SWNT thin films
- **Partners**: 3 from EU and 3 from Japan
- **Main results** for TCF, TFTs and solar cells
- **Future plans** – how to use the results

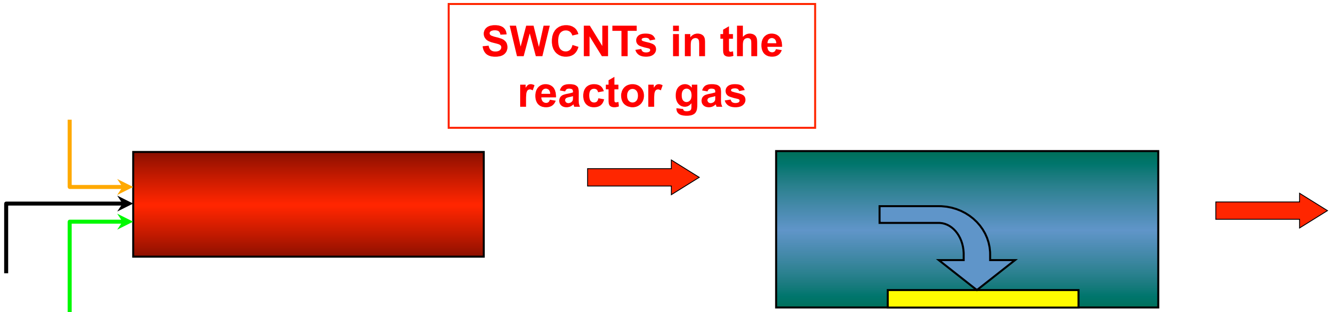
Aalto University novel dry, direct CNT film deposition method: *DPP – Direct Dry Printing*

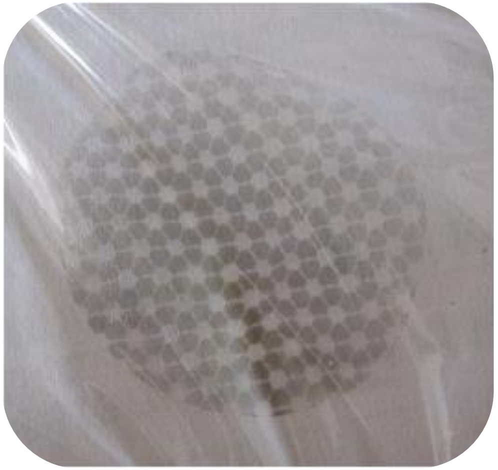
Industrial manufacturing – Canatu Oy

Synthesis

Deposition

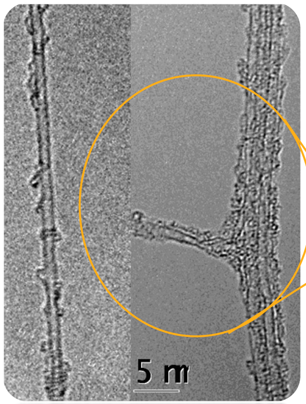
Thin Films

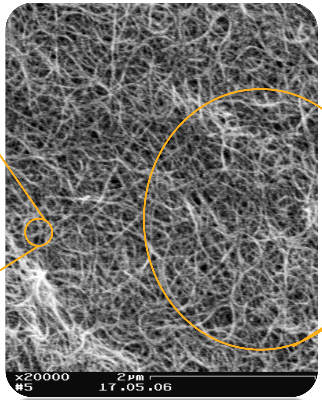


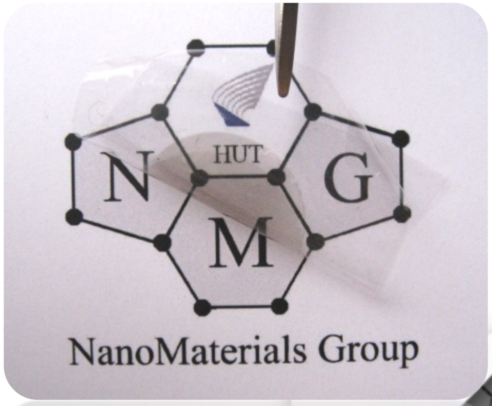


Control of SWCNT properties

Patterned/non-patterned







Heterojuction Solar Cell

THE UNIVERSITY OF TOKYO 東京大学

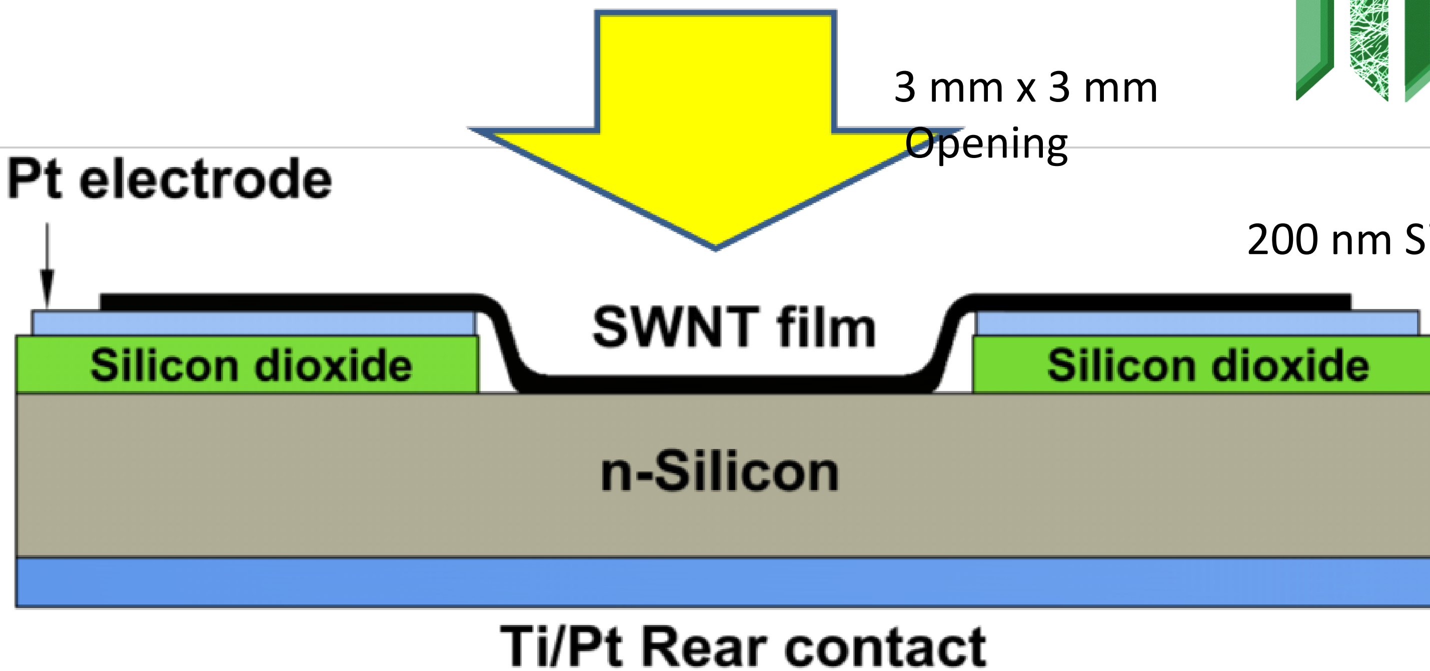
Aalto University

n-type Si (7.5-12.5 Ωcm, ~10^{15} cm^{-3})
With 100 nm SiO_2
5 M NaOH at 90 ˚C for 30min
RCA 2 Cleaning

100mW/cm² AM1.5G illumination

IRENA
Indium Replacement by Single-Walled Carbon Nanotube Thin Films

3 mm x 3 mm Opening



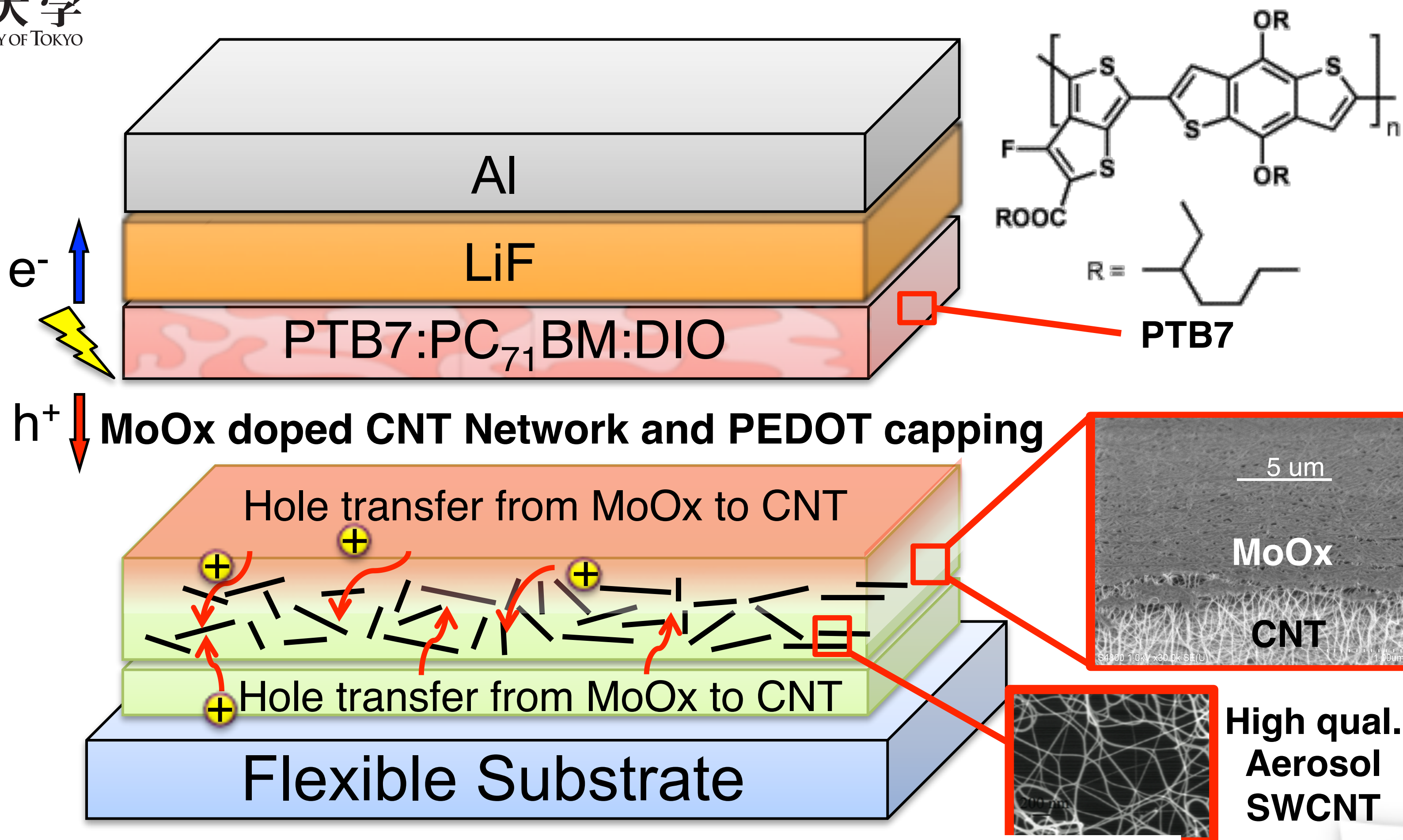
200 nm SiO_2, 100 nm Pt

Ti 10 nm, Pt 50 nm

東京大学
THE UNIVERSITY OF TOKYO

Organic Solar Cell

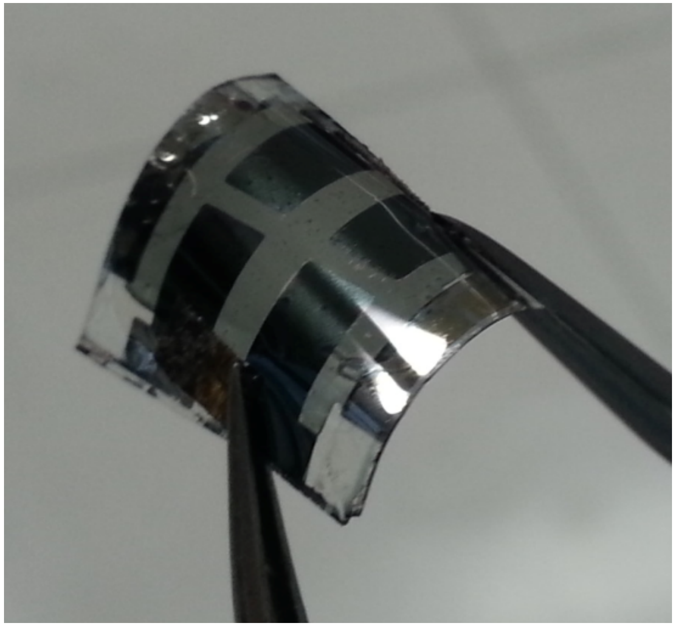
Aalto University

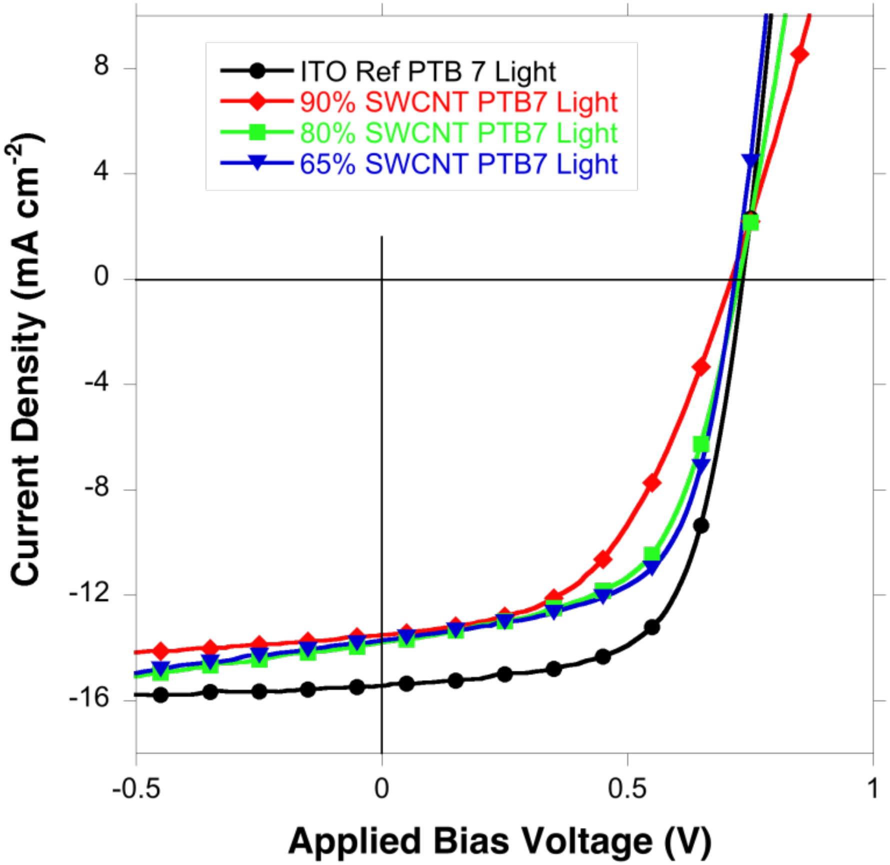


Il Jeon, K. Cui, T. Chiba, A. G. Nasibulin, E. Kauppinen, S. Maruyama, Y. Matsuo (2015)

IRENA
Indium Replacement by Single-Walled Carbon Nanotube Thin Films

Organic Solar Cell





Il Jeon, K. Cui, T. Chiba, A. G. Nasibulin, E. Kauppinen, S. Maruyama, Y. Matsuo (2015)

Anode	V_{OC} (V)	J_{SC} (mA/cm²)	FF	Rs (Ω)	Rsh (Ω)	PCE (%)
ITO	0.74	15.45	0.64	92.0	2.85E+06	7.31
SWCNT 90%	0.71	13.51	0.50	137	7.46E+04	4.79
SWCNT 80%	0.73	13.79	0.57	116	9.77E+03	5.77
SWCNT 65%	0.72	13.72	0.61	51.6	1.22E+04	6.04

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Aalto University

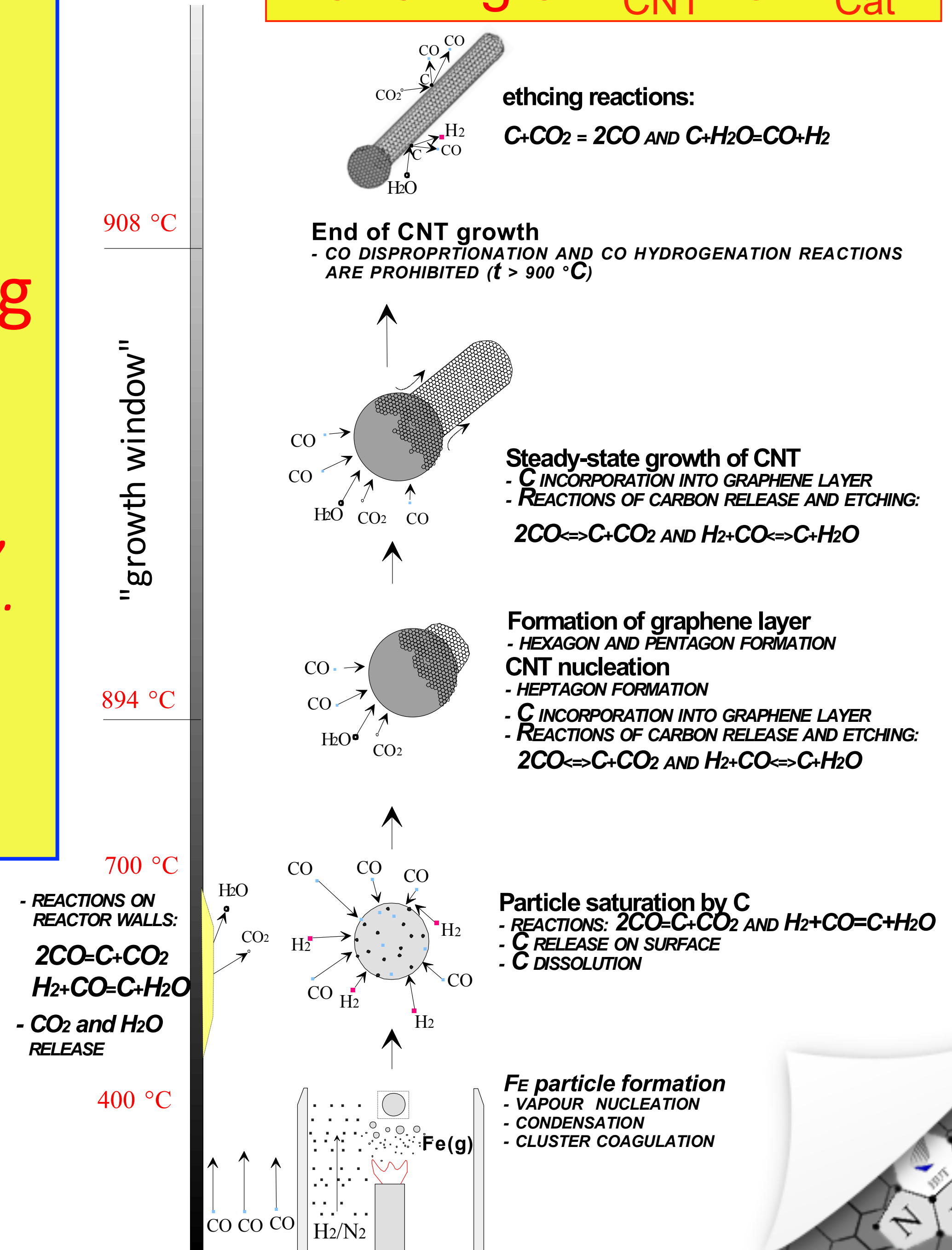
IRENA Indium Replacement by Single-Walled Carbon Nanotube Thin Films

Schematics of formation mechanism during FC-CVD CO using Fe clusters

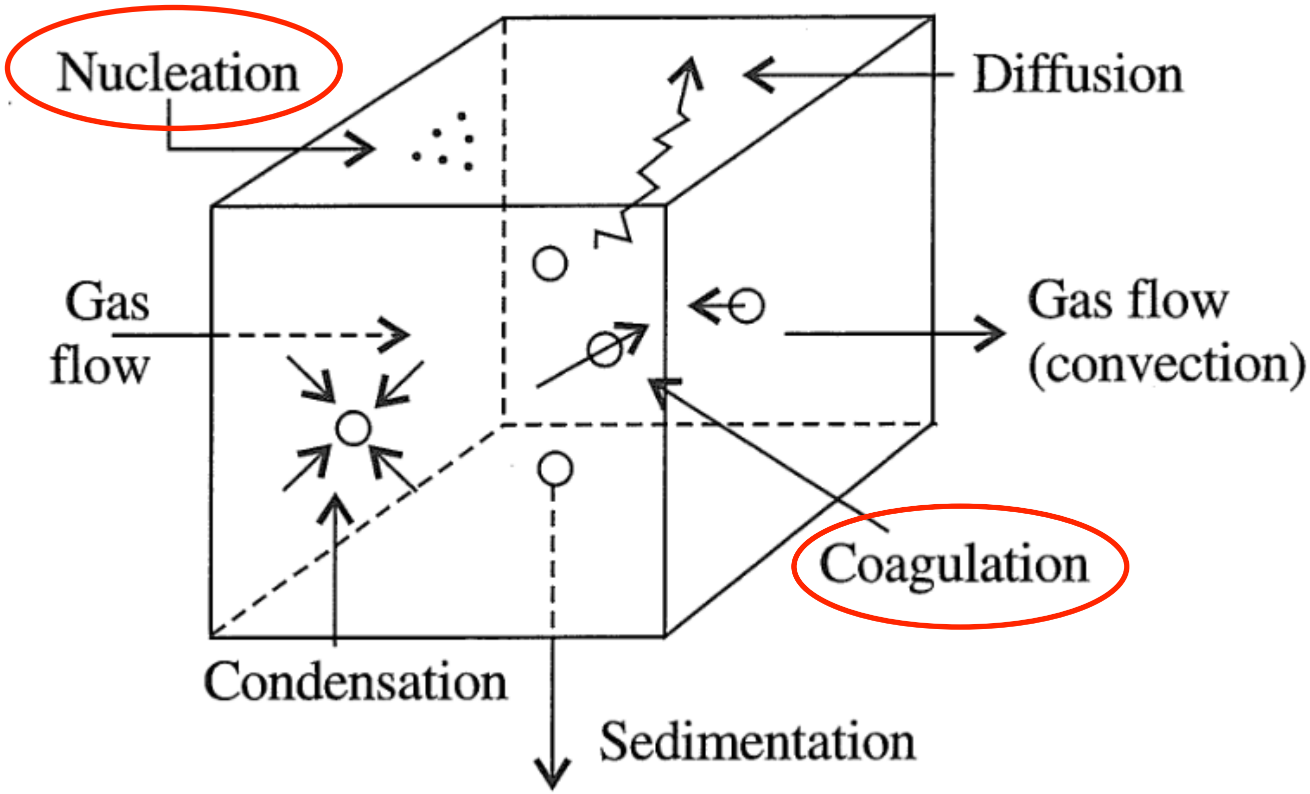
Nasibulin, Queipo, Shandakov, Brown, Jiang, Pikhitsa, Tolochko, Kauppinen, *J. Nanosci. Nanotech.* **6** 1233.

Controll :
- Diameter and length via temperature and oxidant (e.g. CO_2, NH_3, H_2O) concentration
- Bundling via catalyst concentration

Bundling α N_{CNT}^2 α N_{Cat}^2



Fundamentals of particles in gas dynamics – how catalyst particles and nanotubes behave during the floating catalyst CVD synthesis



Processes tacking place in an elemental volume in the general dynamic equation. Gas flow produce particle transport across the element boundaries. In addition to gravitation, other force field can drive the fluxes, i.e. electrical potential, temperature gradient.

Basic dynamical processes in aerosol systems

Aerosol are physically unstable systems experiencing the continual influence of various dynamic processes. These processes change the aerosol properties, such as particle size and charge distribution, particle morphology, and so on. **N = number concentration in the FC-CVD gas**

General dynamics equations:

$$\frac{dN_k}{dt} = J(t)\delta_{i,k} + \frac{1}{2}\rho_g \sum_{j=1}^{k-1} \beta_{k-j,j} N_{k-j} N_j - \rho_g \beta_k N_k \sum_{j=1}^{\infty} N_j +$$

Nucleation of Catalyst particles

Collisions – catalyst particles and SWNTs

$$+\rho_g\left(\beta'_{1,k-1} N'_1(t) N_{k-1} - \beta'_{1,k} N'_1(t) N_k\right)$$

Condensation of catalyst metal vapour on SWNTs and on non-active catalyst particles

β – the coagulation kernel (coefficient) if two colliding particles,
$\delta_{i,k}$ – Kroneker delta ($\delta_{i,k}$ =1 for i=k, $\delta_{i,k}$ =0 otherwise),
ρ_g – the carrier gas density, N'_1- number concentration of condensing monomers.
β ‘– the collision frequency of monomers and particles,

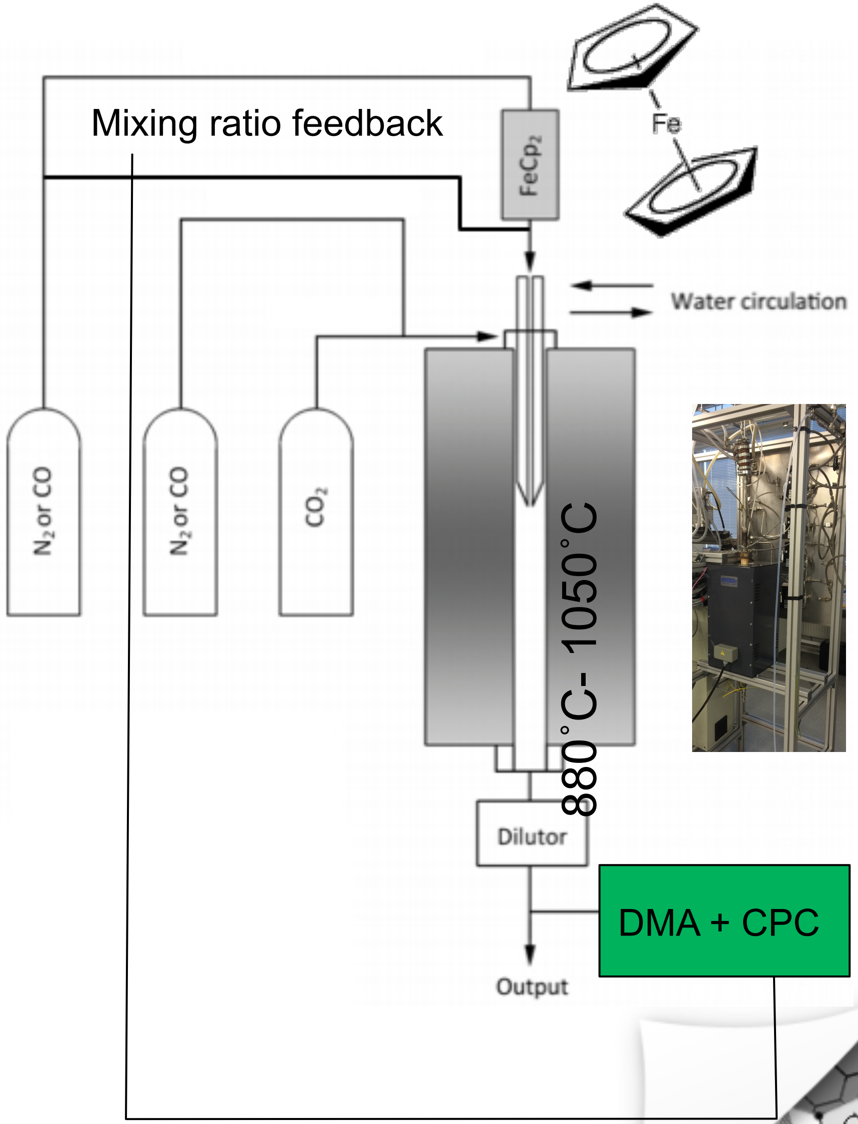
Catalyst concentration Controlled FC-CVD with Concentration Monitoring – New Reactor

- CO as carrier gas and carbon source with ferrocene and CO_2
- Particle formation by thermal decomposition of ferrocene
- SWCNTs grown in the gas flow via Bouduard reaction

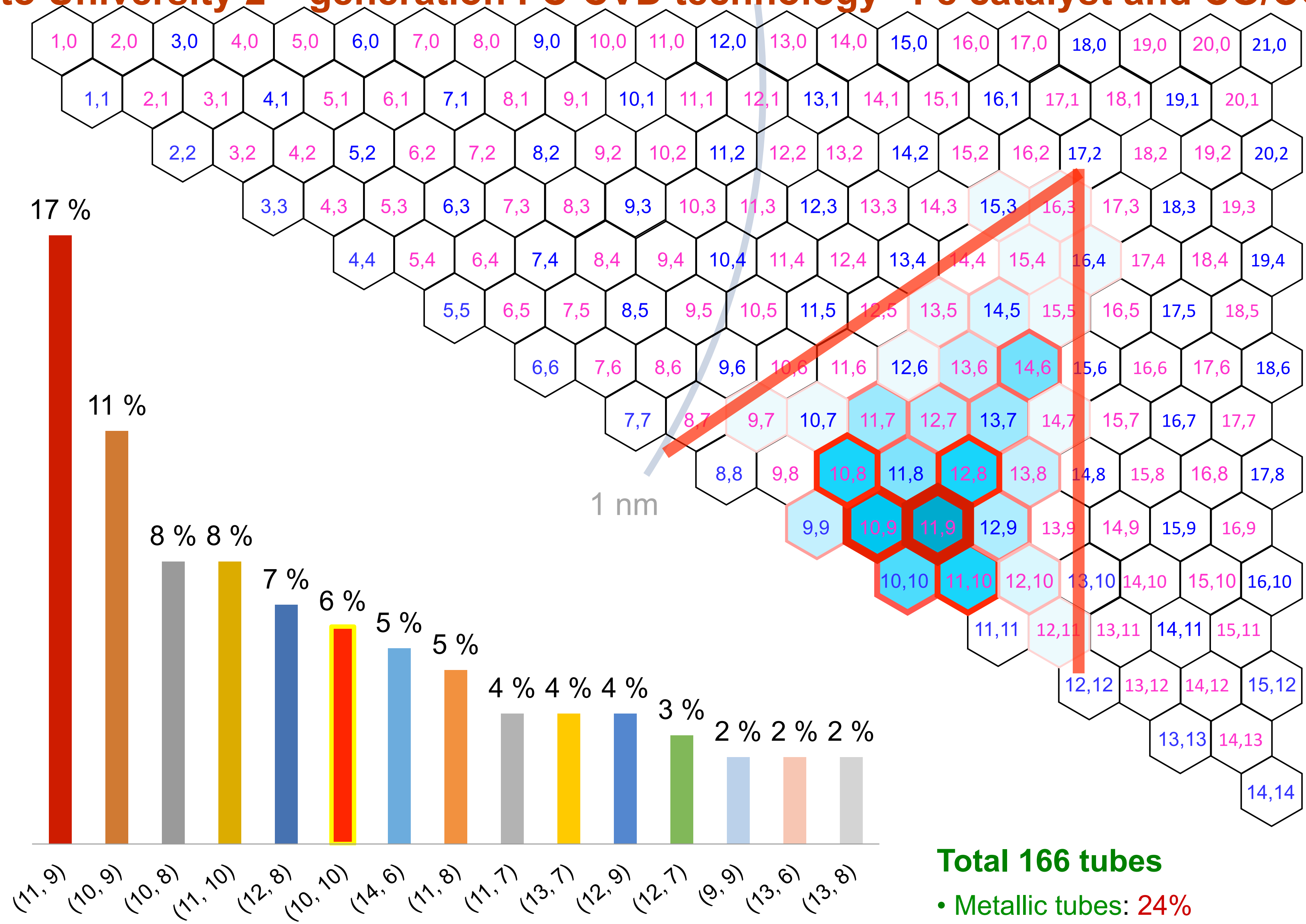
$$CO + CO \overset{Fe}{=} C(s) + CO_2$$

- Controlled concentration
  - 1e4 - 1e6 #/cm^3
  - High individual SWCNT fraction
- Substantially improved
  - Stability
  - Performance

A. Kaskela et al. (2015)To be submitted



Aalto University 2nd generation FC-CVD technology– Fe catalyst and CO/CO_2



Total 166 tubes

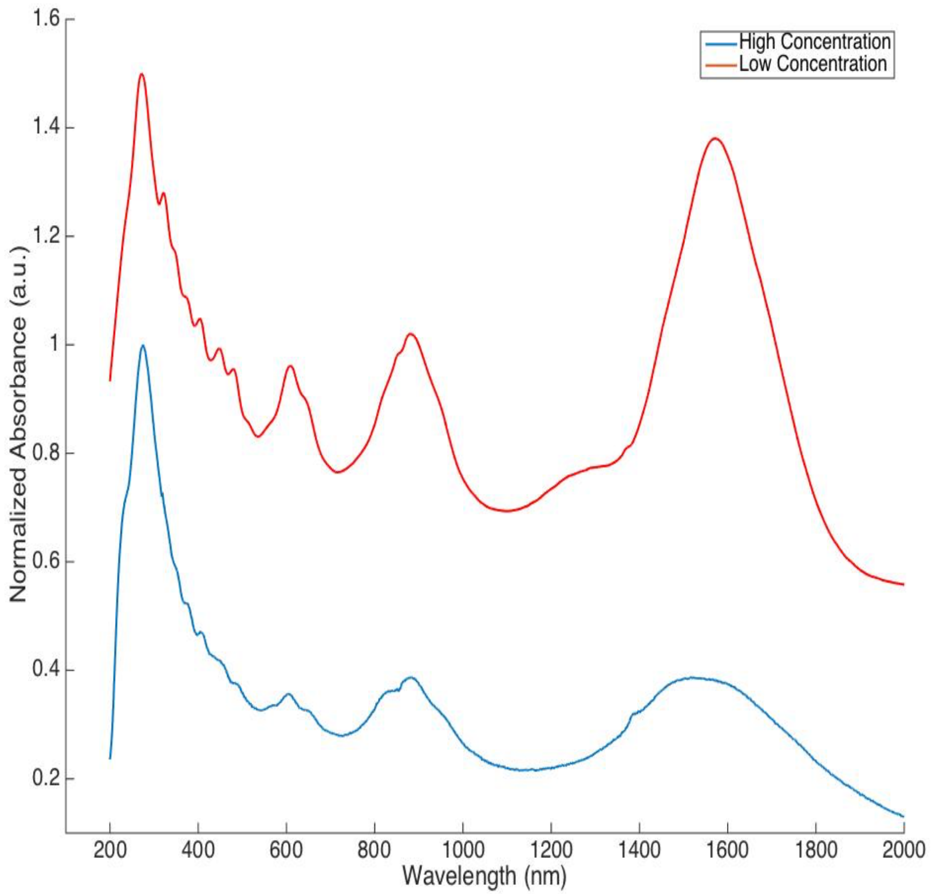
- Metallic tubes: 24%
- Semiconducting tubes: 76%

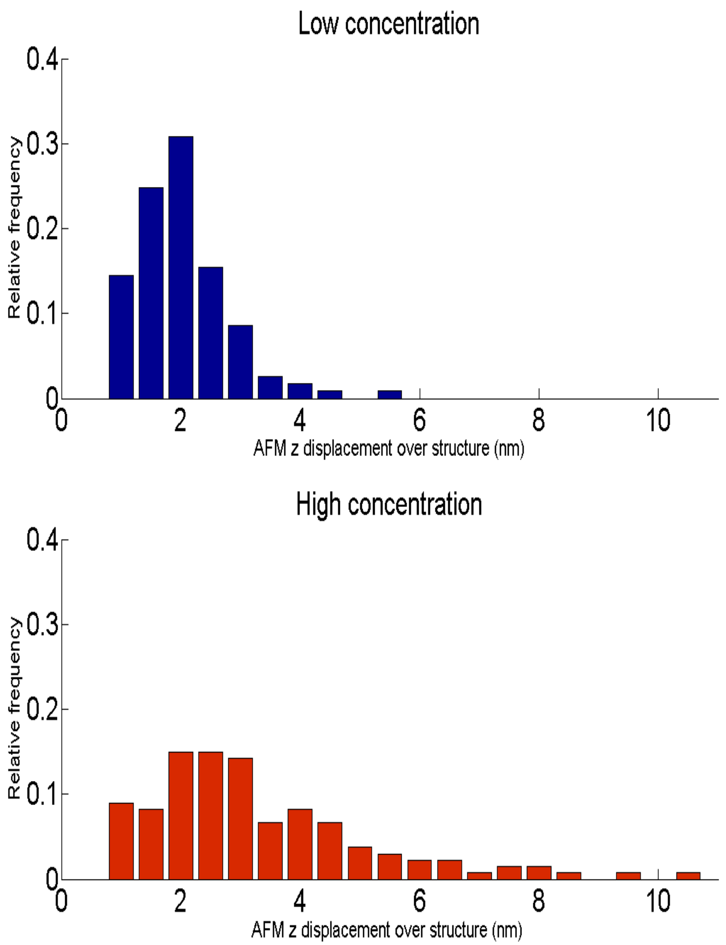
Note: Nanotubes with the occurrence rate less than 2% are not shown in the chat.

Jiang, H., Kaskela A. et al. (2015) In preparation

Optical Absorption Spectra of as-produced SWNT Thin Films

Bundle Diameter Distribution from AFM

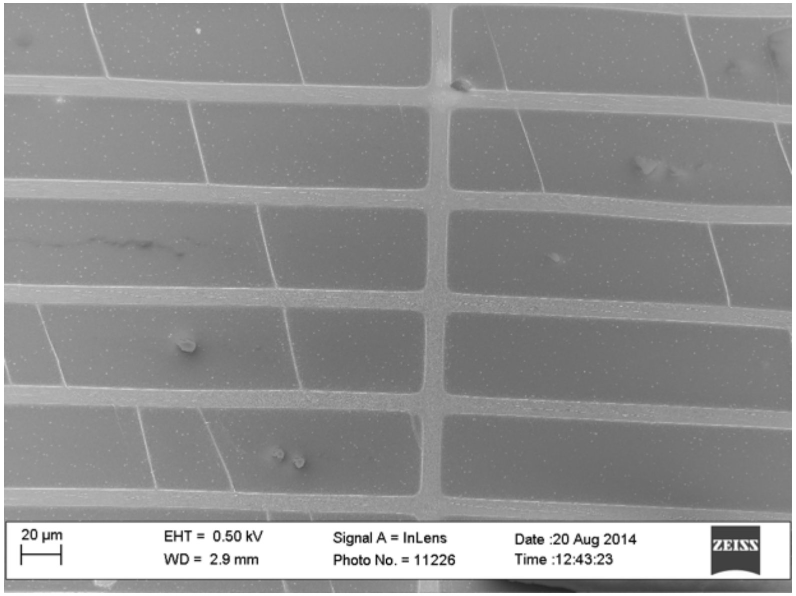


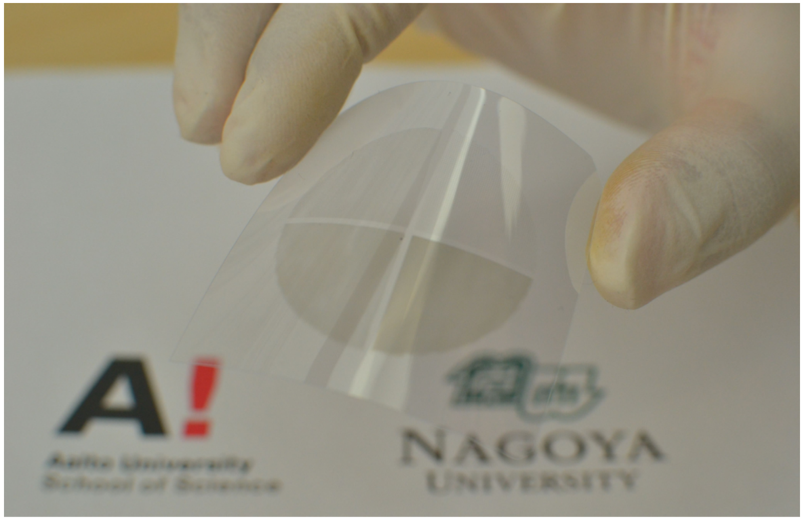


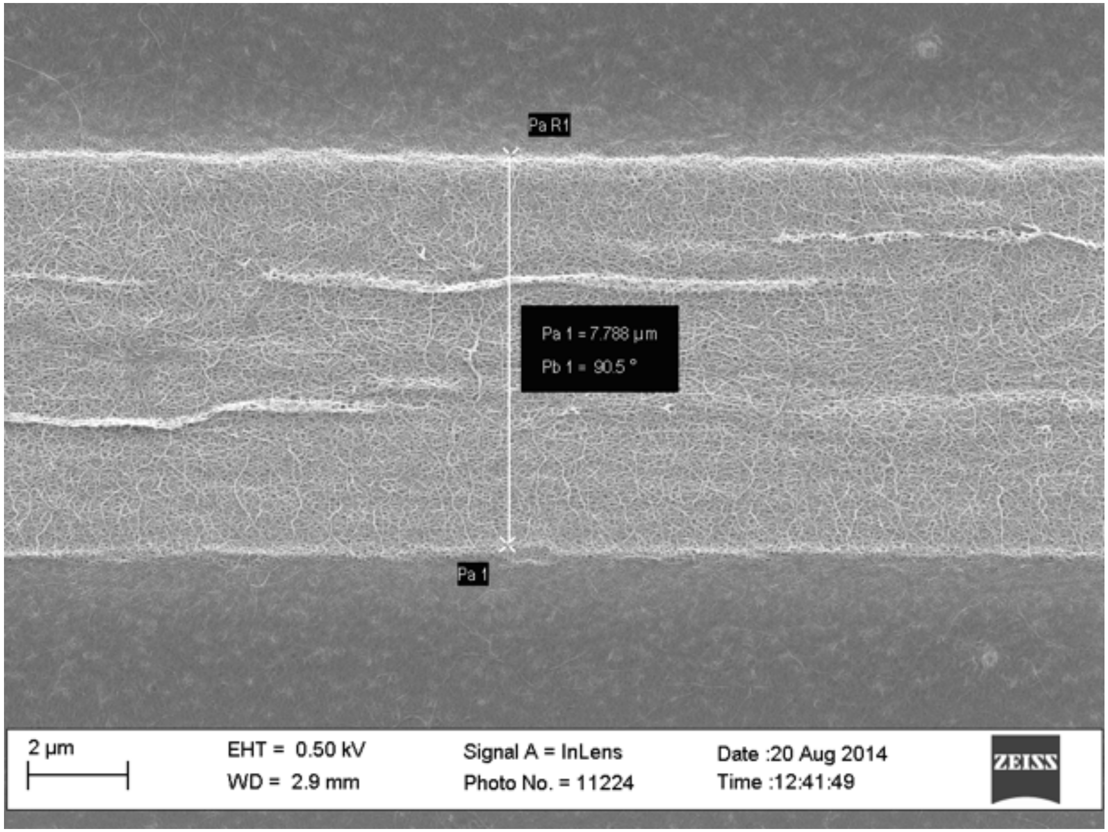
A. Kaskela, P. Laiho et al. (2015) To be submitted

Micropatterned SWNT TCFs – 67 ohms/sq @ 97 % T

N. Fukaya, D. Y. Kim, S. Kishimoto, S. Noda, and Y. Ohno, "One-Step Sub-10 μm Patterning of Carbon-Nanotube Thin Films for Transparent Conductor Applications," ACS Nano, Apr. 2014.



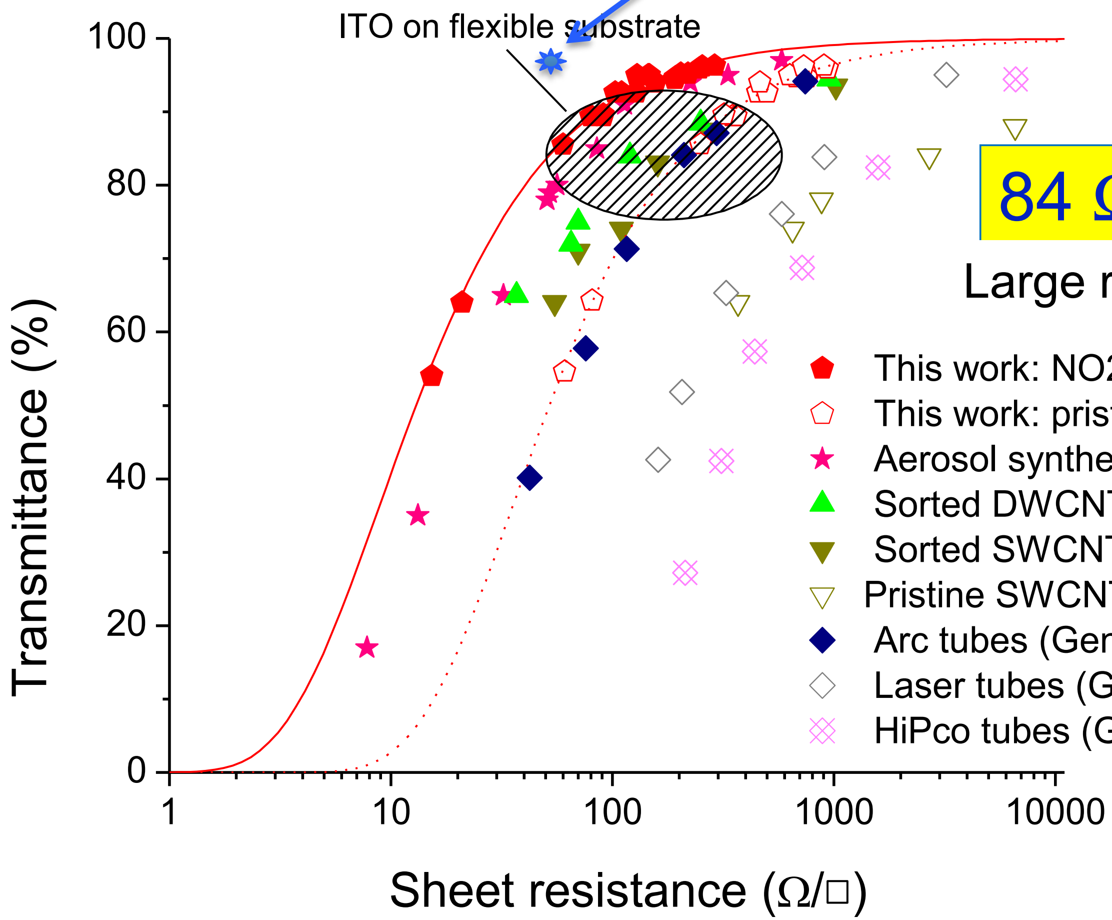




A. Kaskela, Y. Ohno et al. (2015) To be submitted

With micropattern: 67 ohm/sq @ 97 %T - collaboration with Prof. Yutaka Ohno

Record performance level of SWCNT-based transparent electrodes (1.7 nm tubes)

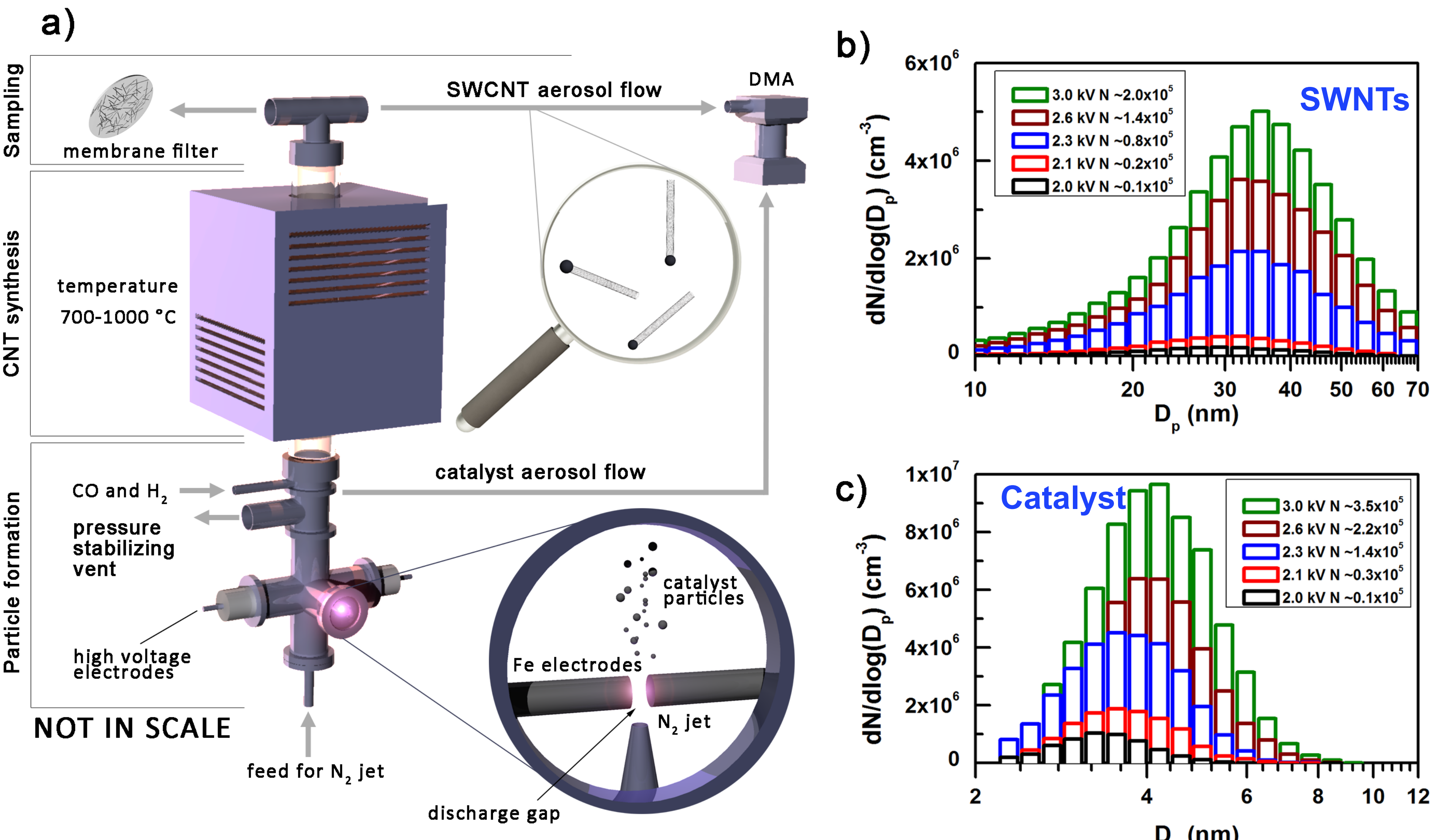


84 Ω/□ at Tr=90%

Large reactor – 10 nm bundles

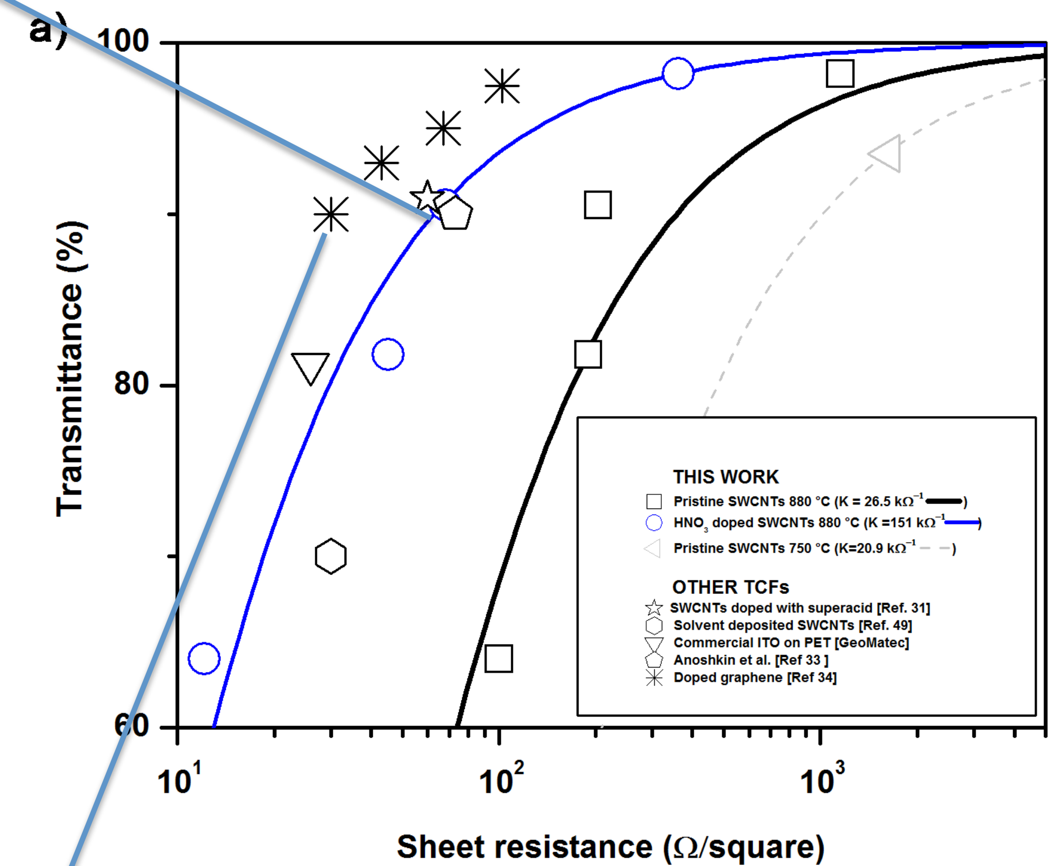
Nasibulin, Kaskela, Mustonen, Anisimov, Kauppinen, *et al.* (2011) *ACS Nano, 5(4), p.3214*

Novel spark discharge FC-CVD SWNT technology – separate catalyst formation and SWNT nucleation - bundling control



K. Mustonen et al. (2015) Submitted

TCF with Individual tubes – length 4 microns – 60 ohms/sq @ 90 % T (HNO$_3$ doped)

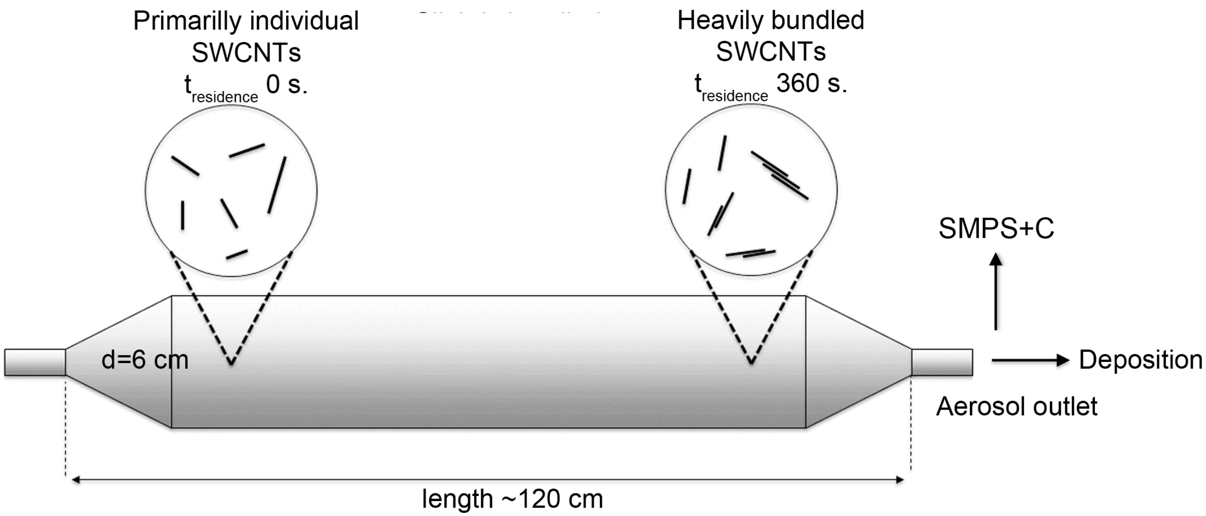


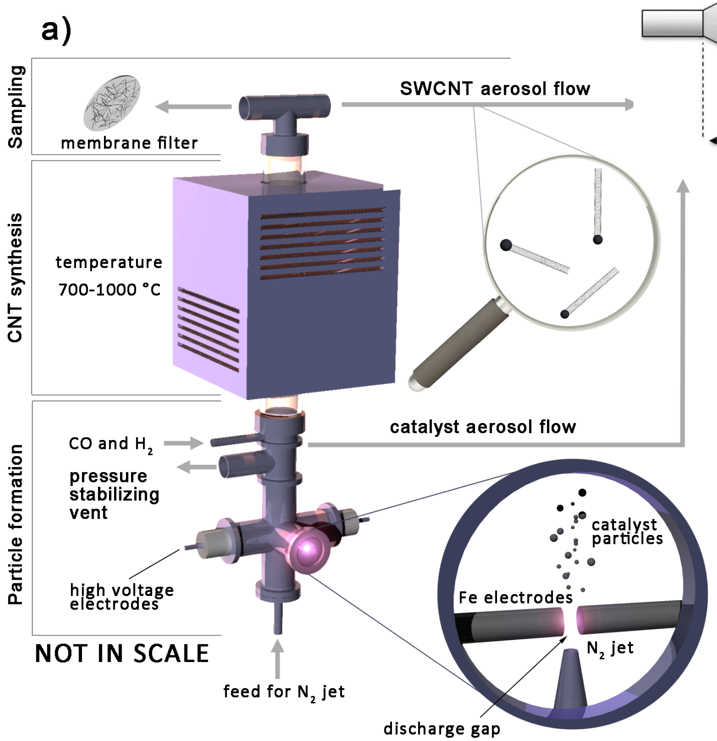
Note: Graphene ✳ 30 ohms/sq @ 90 % T - has been transferred 4 times from Cu substrate

K. Mustonen, P. Laiho, A. Kaskela, H. Jiang, A. Nasibulin, E.I. Kauppinen (2015) In preparation

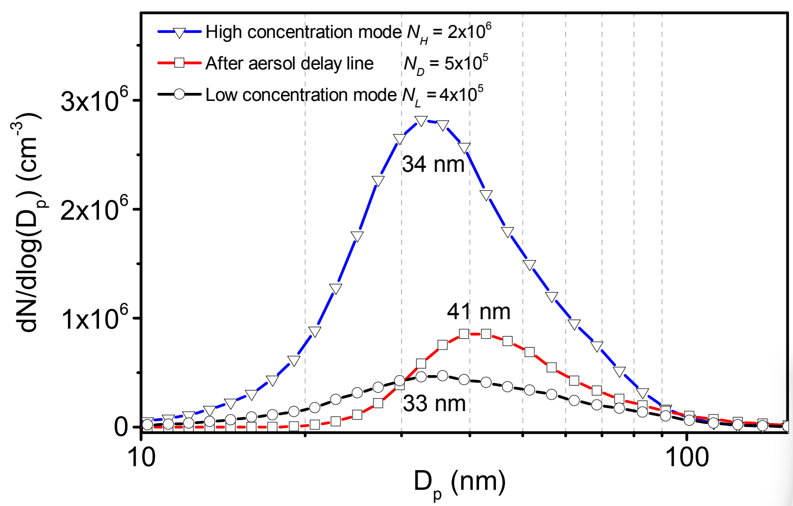
SWNT bundling in the laminar flow reactor – 0 to 360 s delay time.

Spark discharge Fe catalyst in N_2-H_2-CO FC-CVD – low and high SWNT number concentration





Gas phase SWNT number size distributions based on electrical mobility

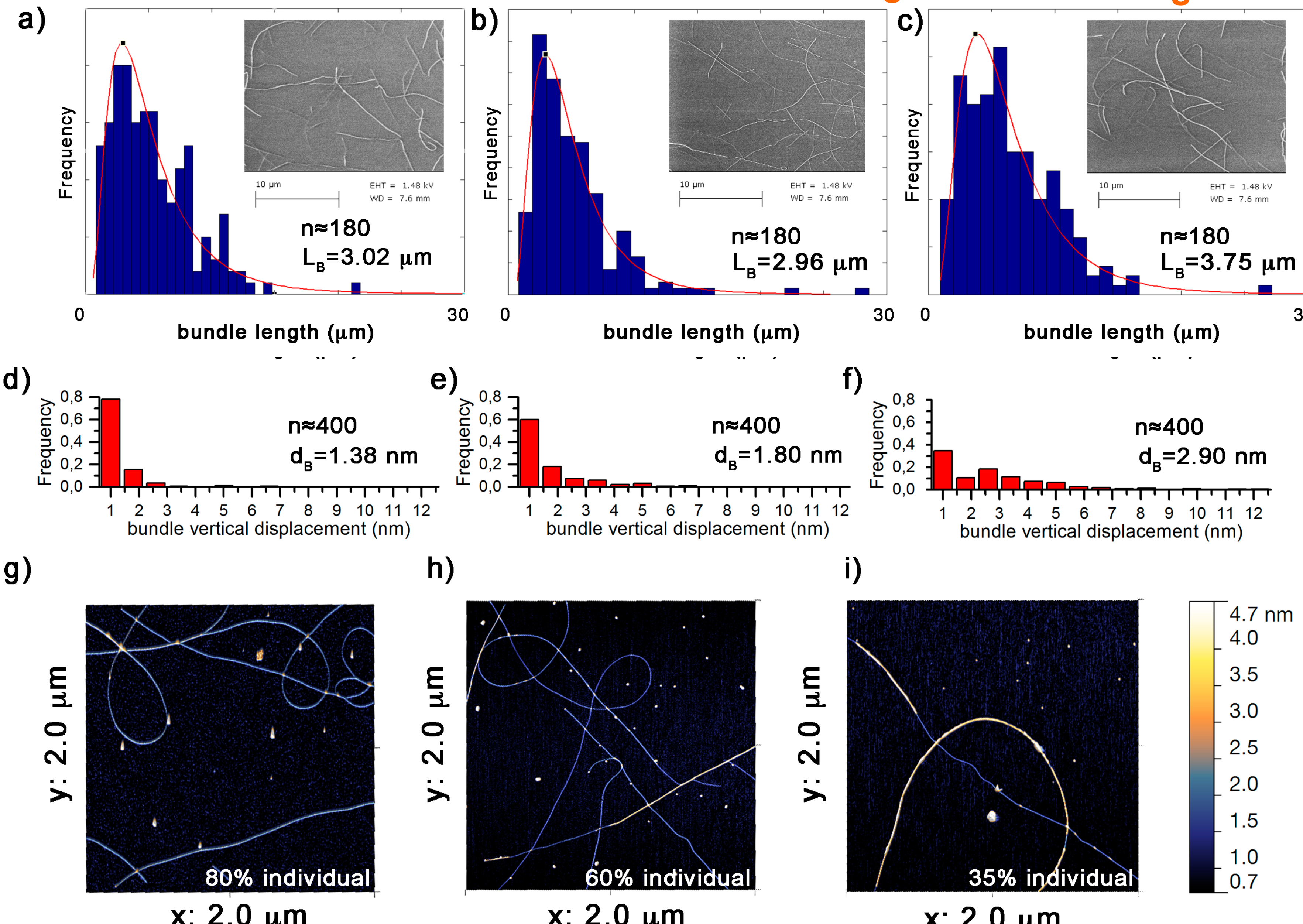


K. Mustonen, P. Laiho, A. Kaskela, H. Jiang, A. Nasibulin, E.I. Kauppinen (2015) In preparation

Low concentration
No additional bundling

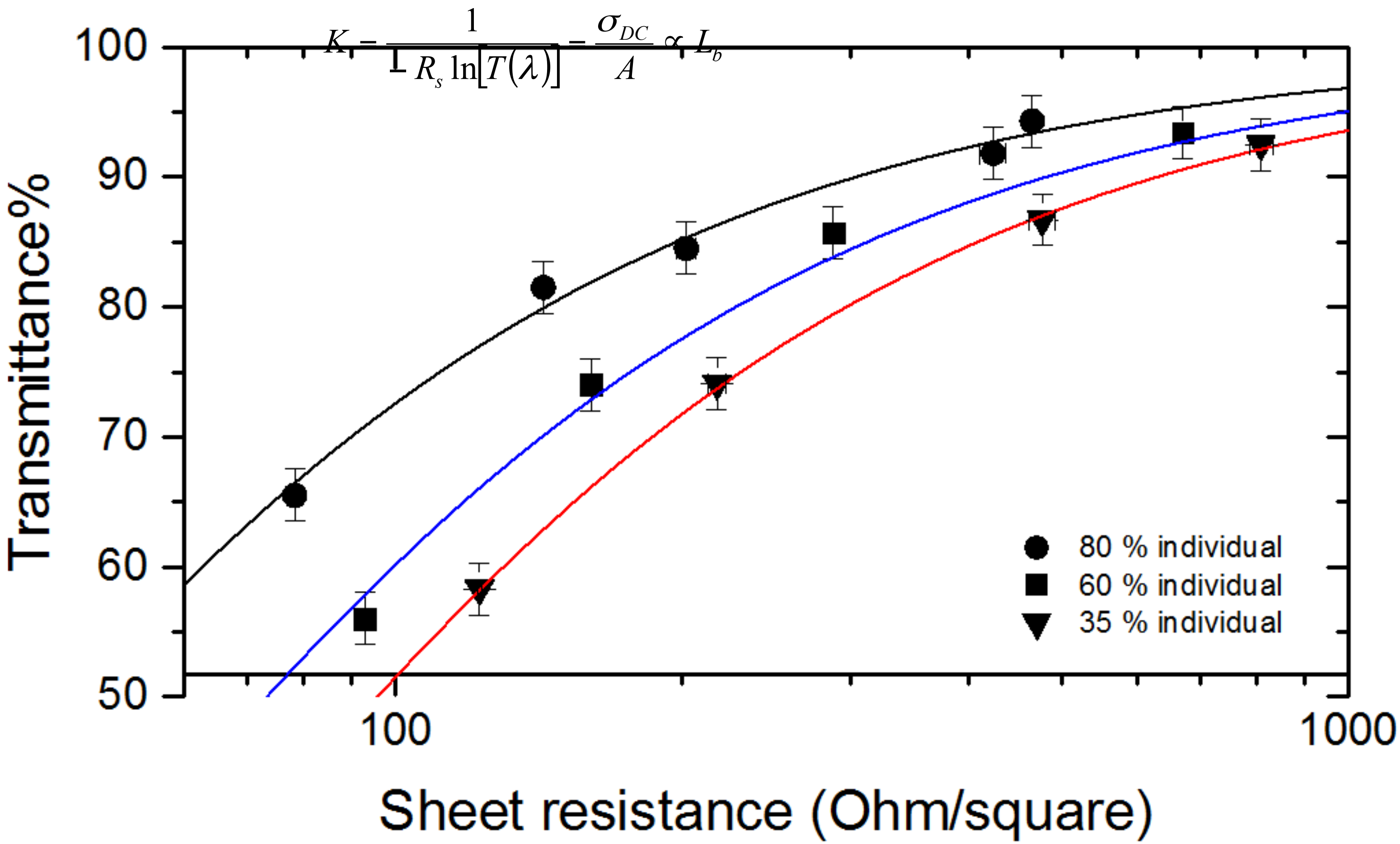
High concentration
No additional bundling

Low concentration
360 s bundling time



K. Mustonen, P. Laiho, A. Kaskela, H. Jiang, A. Nasibulin, E.I. Kauppinen (2015) In preparation

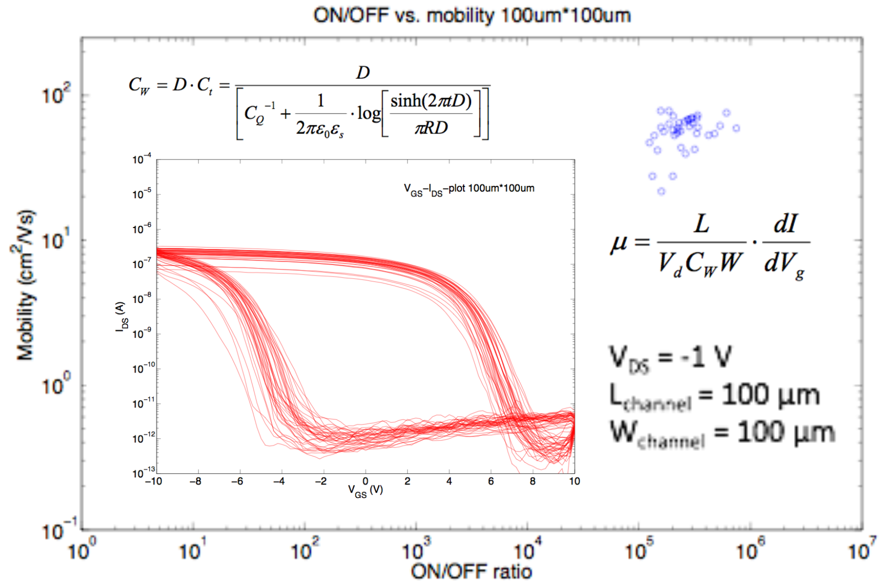
The effect of bundling on sheet resistance vs. transmittance – non-doped films



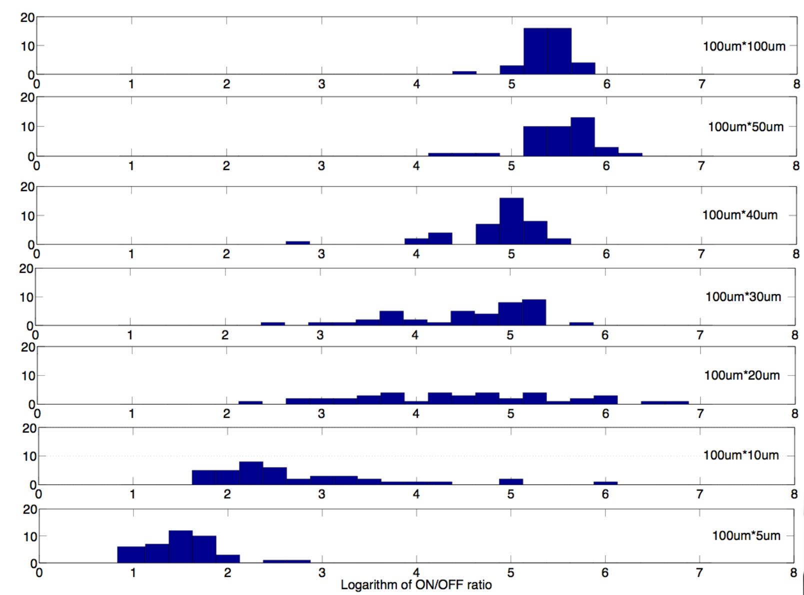
K. Mustonen, P. Laiho, A. Kaskela, H. Jiang, A. Nasibulin, E.I. Kauppinen (2015) In preparation

TFT-FETs
Spark FC- CVD SWNT random network via filter transfer

- Excellent SWCNT network uniformity
  - High device yield and controlled transfer characteristics
- The charge carrier mobility ~100cm^2/Vs and typical ON/OFF ratios >10^5
- Small ON current spread
- ON/OFF ratios scaling as function of channel length
  - SWCNT network uniformity approaches ideal random network with 1/3 metallic and 2/3 semi-conductive SWCNT



Kang et.al. Nature Nanotech, 2007.



K. Mustonen, P. Laiho, A. Kaskela, H. Jiang, A. Nasibulin, E.I. Kauppinen (2015) In preparation

Content

- **The need** to replace Indium and Gallium in transparent conductors (TCF) and transistor (TFT): carbon nanotubes as novel materials for flexible, transparent and stretchable electronics ?
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- **Partners**: 3 from EU and 3 from Japan
- **Main results** for TCF, TFTs and solar cells
- **Future plans** – how to use the results

Companies following IRENA

From EU:

- Osram
- Nokia Oy
- Canatu Oy
- Fortum Oy
- Sefar AG
- Beneq Oy
- Amcor
- Eight19 Ltd

From Japan:

- Showa Denko K.K.
- Toray

ACKNOWLEDGEMENTS:

PRINTED TOUCH SENSORS USING CARBON NANOBUD® MATERIAL

Anton S. Anisimov*, David P. Brown*, Bjørn F. Mikladal*, Liam Ó Súilleabháin*, Kunjal Parikh**, Erkki Soininen*, Martti Sonninen*, Dewei Tian*, Ilkka Varjos*, Risto Vuohelainen*

* Canatu Oy, Finland

** Intel Corporation, USA

www.canatu.com

CANATU

Touch the Future

Canatu's production facility

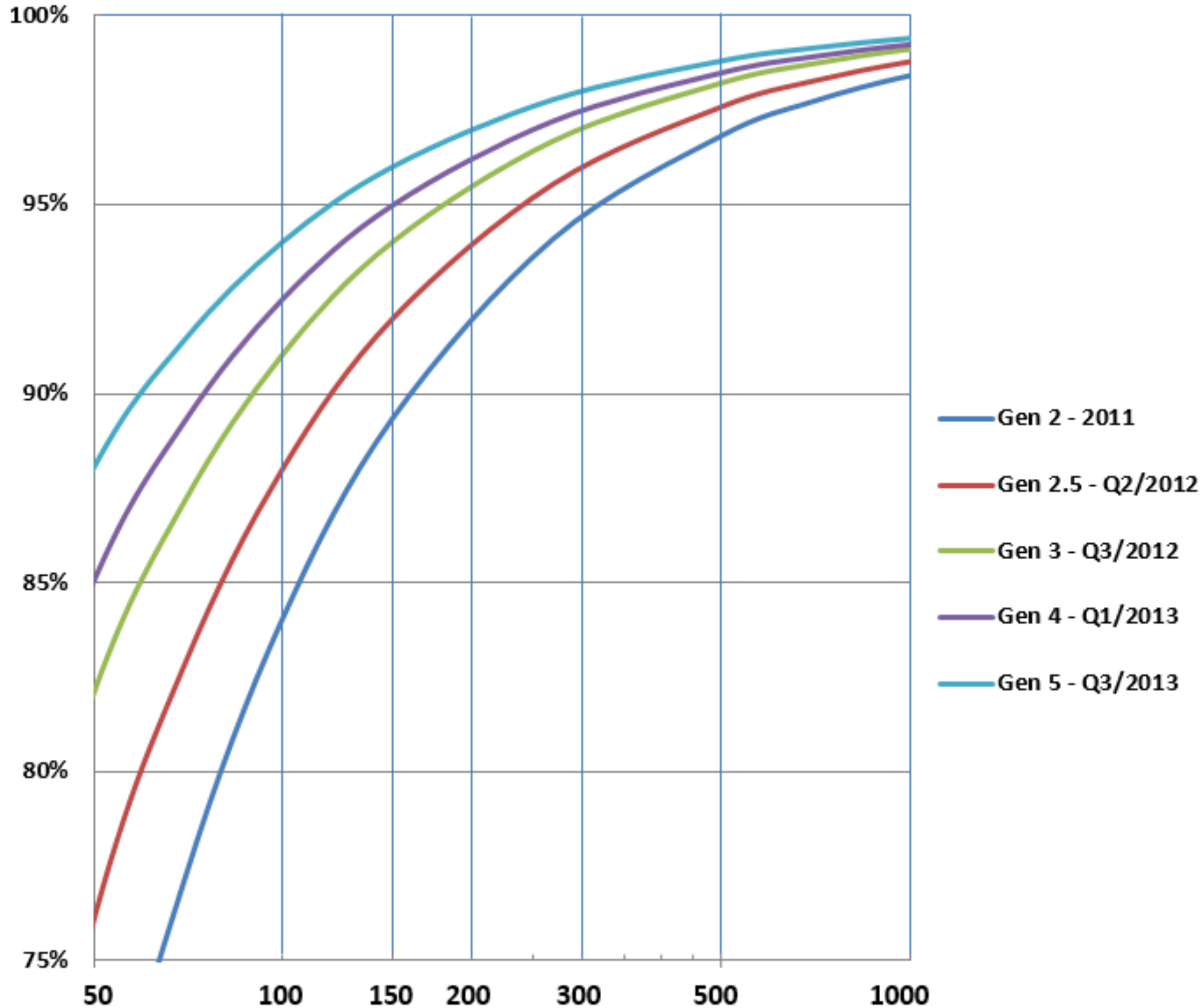
- In Helsinki, Finland

- Roll-to-roll 600mm wide CNB™ Films
- 1200 m^2 production space
- 400 m^2 clean room

- Canatu is
  ISO 9001:2008 certified

QUALITY SYSTEM CERTIFICATION
DNV·GL
ISO 9001

Commercially available by Canatu Oy: High transparency nanotube film - meeting ITO stability and uniformity specs



Examples:

100 Ω/□ at 94%
150 Ω/□ at 96%
270 Ω/□ at 98%

This is substrate-normalized transmission:
T = 100% - CNB Absorbance

intel

ATMEL

CANATU

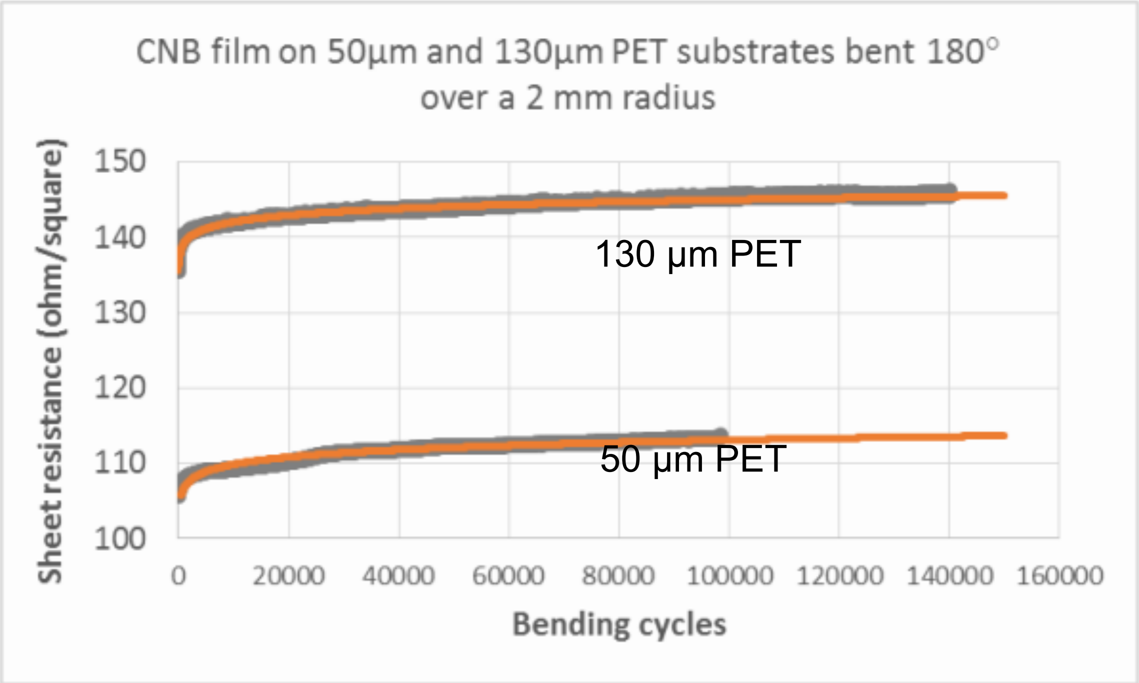
Haze comparison in touch modules

Intel measurements from 13.3" Ultrabooks

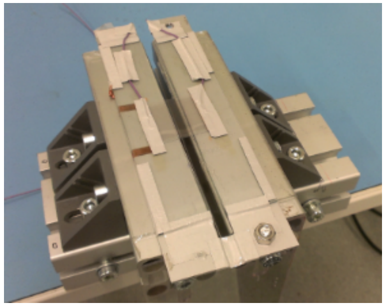
Touch Module	Type	Sensor	Haze (%)
Carbon NanoBud	CNB	GFF	0.6
ITO OGS (no index matching)	ITO	OGS	3.3
Silver nanowires Metal Mesh	Mesh	GFF	1.4
Silver Metal Mesh #1	Mesh	GFF	2.0
Copper Metal Mesh #1	Mesh	GF2	1.6
Copper Metal Mesh #2	Mesh	GF2	2.0
Silver Metal Mesh #2	Mesh	GF2	1.3
IPAD 4 (Air)	ITO	GF2	1.0

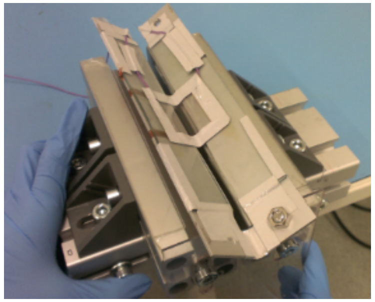
CNB has the lowest haze in the industry

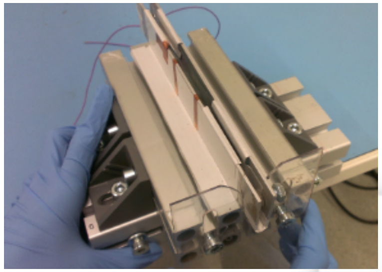
CNB Film lifetime bending test – touch sensors for *flexible devices*



Gray lines are raw values and **orange** lines are fittet values.





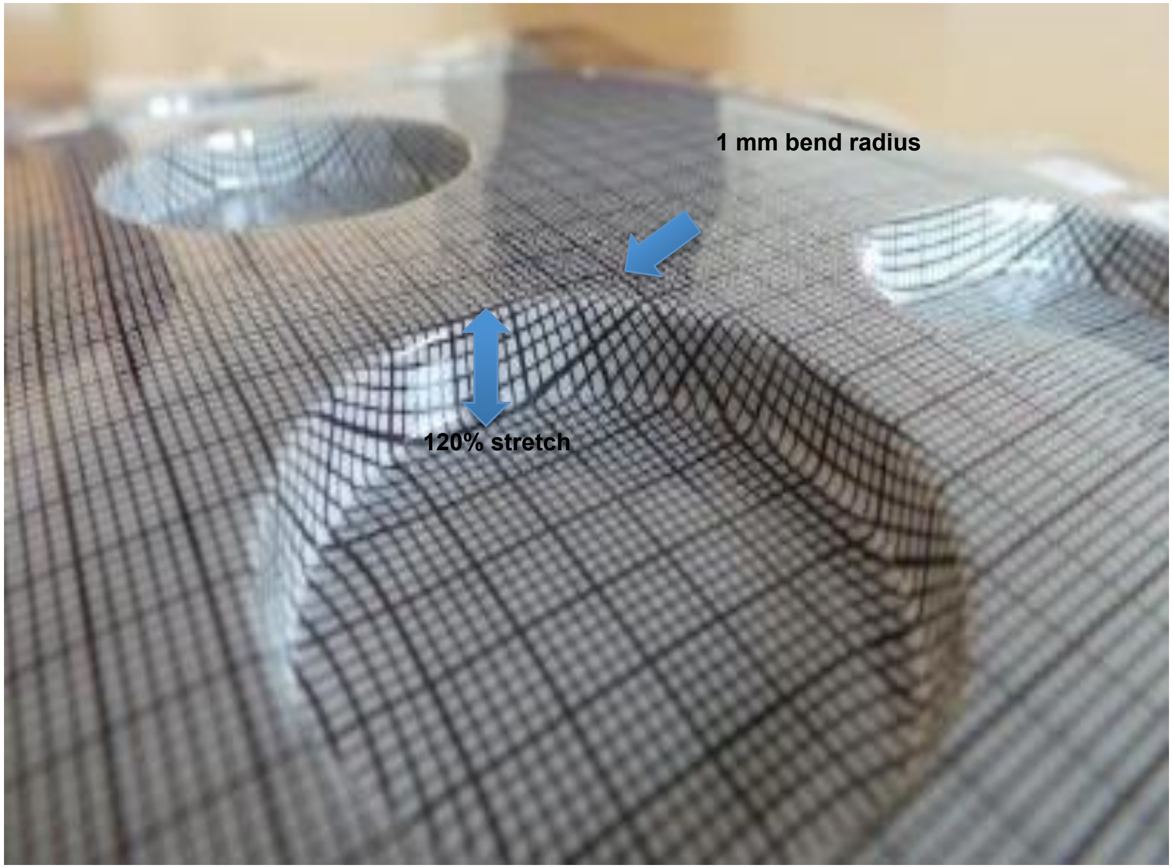


7% resistivity change at 2 mm bending radius over 140 k bending cycles.

CNB survives a lifetime of a foldable device.

CNB™ films can be stretched

- Using Industry-standard forming and injection moulding processes: Pressure forming, Film Insert Molding (FIM)
- Locally streched as much as 120%, bending radius 1 mm
  - CNB™ still remained conductive in the tested challenging forms



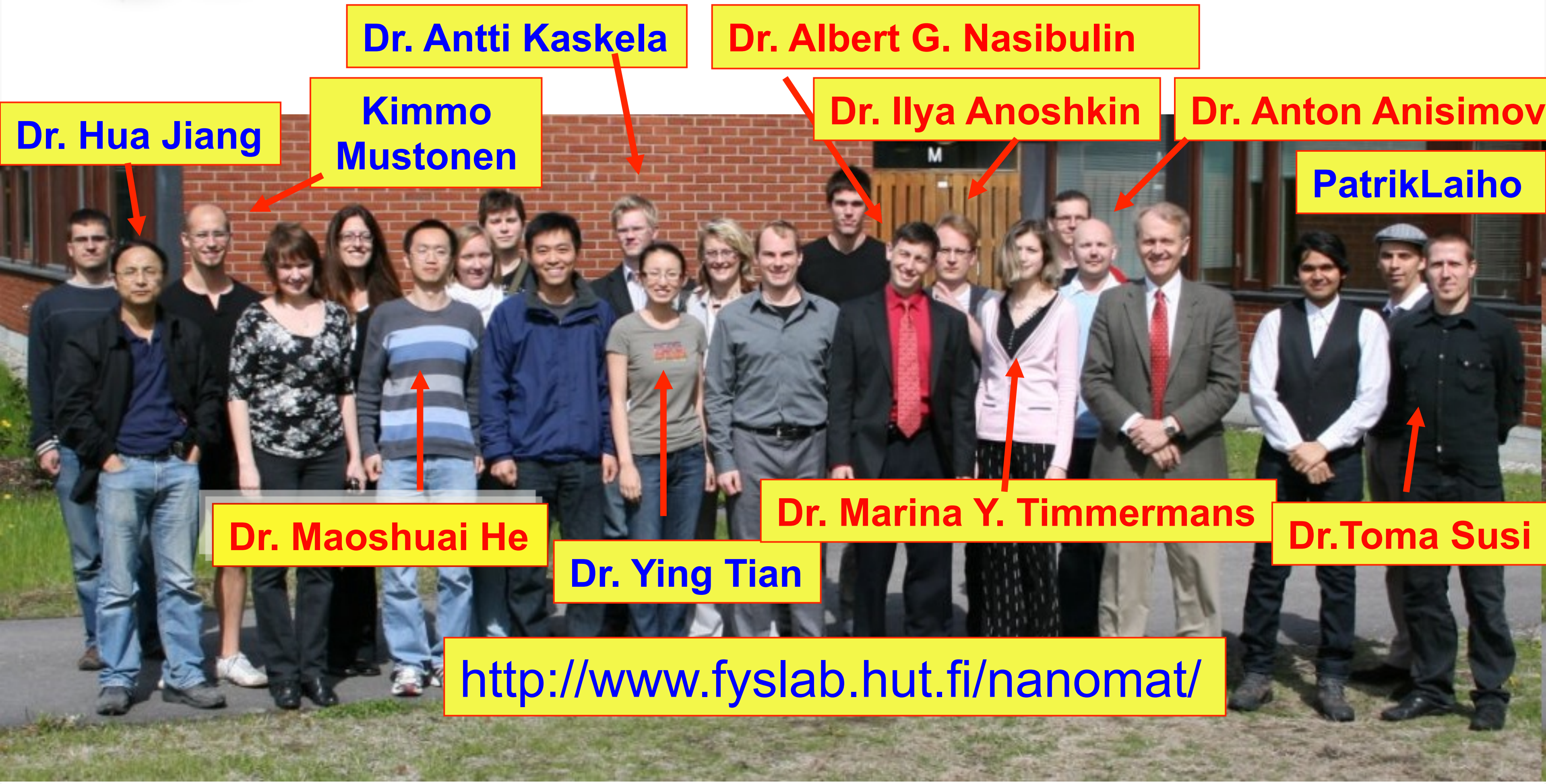
CANATU

Bayer MaterialScience

NanoMaterials Group, Aalto University School of Science

Department of Applied Physics

OPEN POSITIONS ! OPEN POSITIONS !



Acknowledgement for Funding

* Academy of Finland
* EU FP7 TREASORES & IRENA projects
* Aalto MIDE and AEF programs

CANATU

Prof. Y. Ohno, Nagoya University, Japan

IRENA
Indium Replacement by Single-Walled Carbon Nanotube Films

The Canatu Team

Dr. Erkki Soininen


Thank You Very Much for Your Attention !