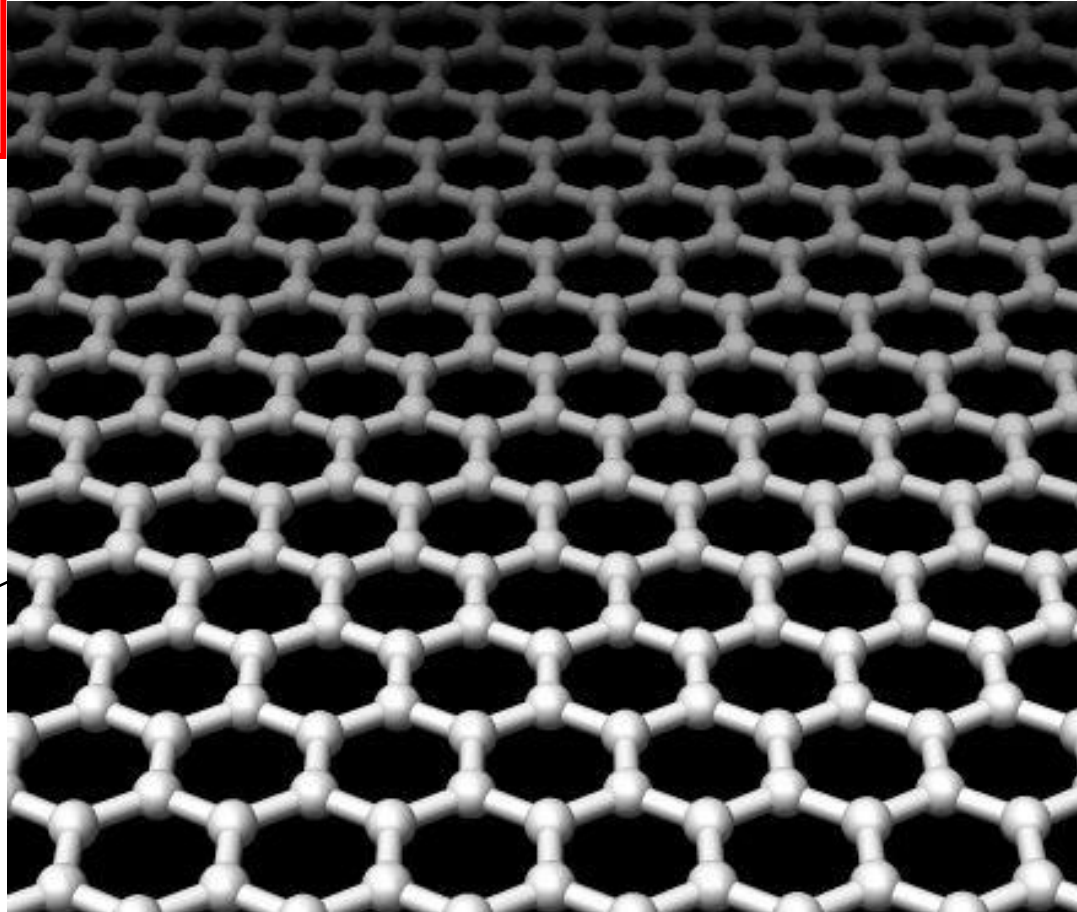
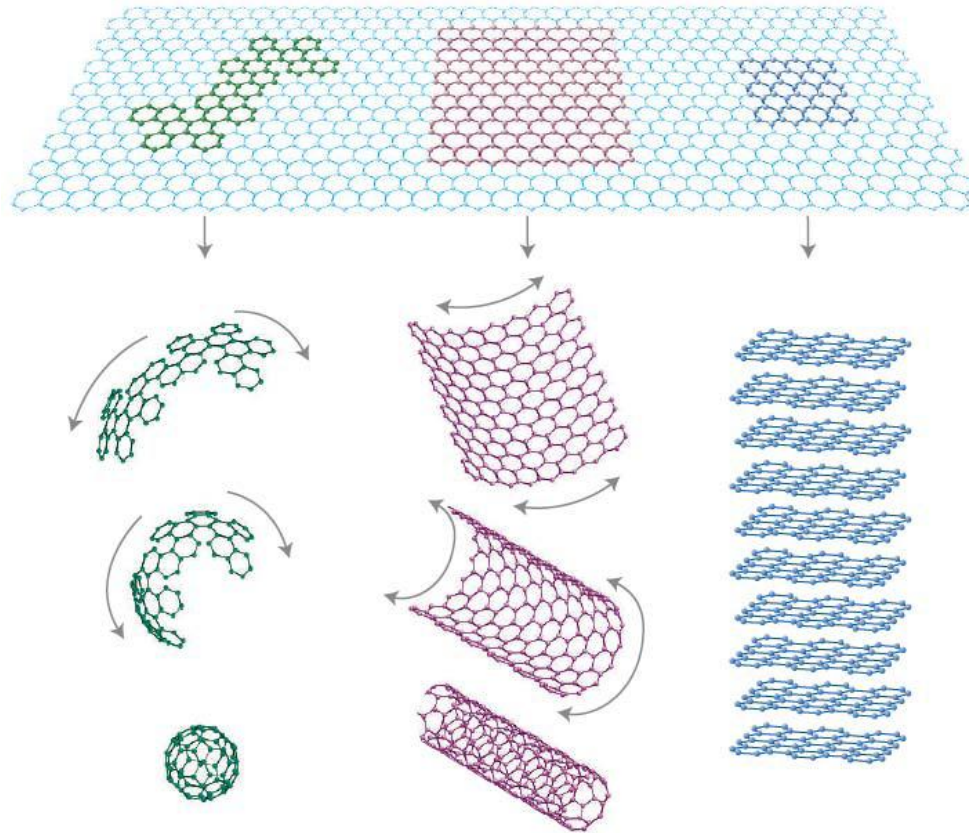


# Lectures 13: Graphene

$R = ?$



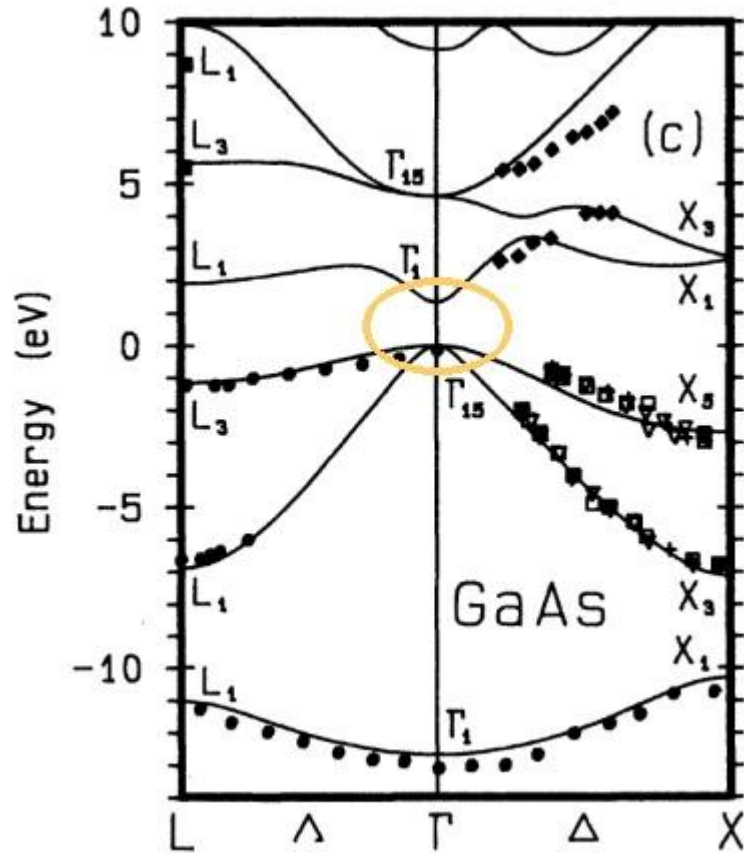
# Allotropes of Carbon



A. Geim and K. Novoselov, "The Rise of Graphene", *Nature Materials*, **6**, 183-191, (2007).

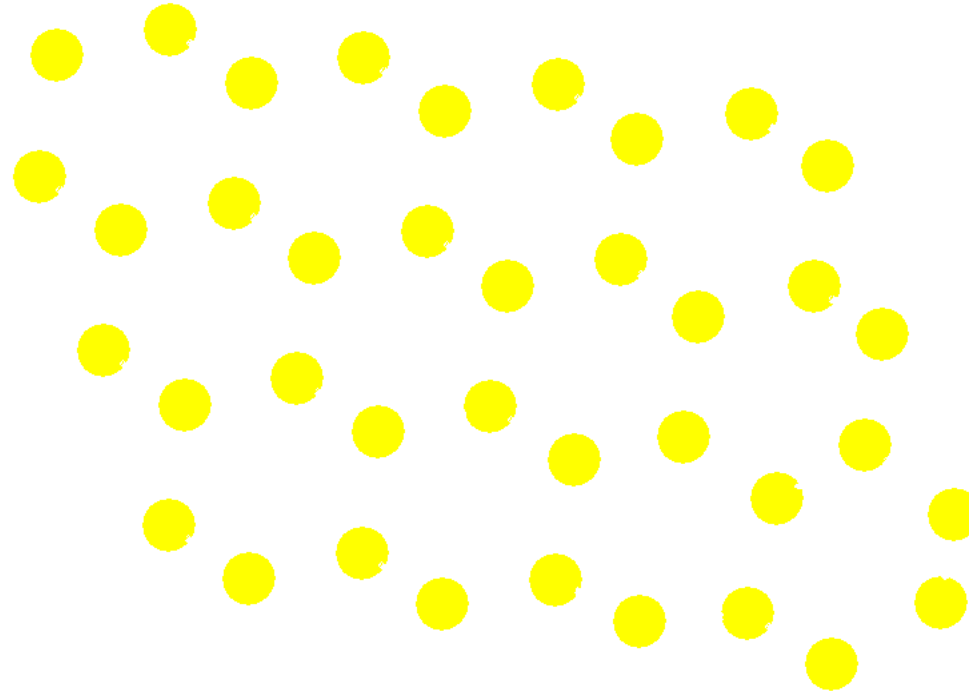


# GaAs



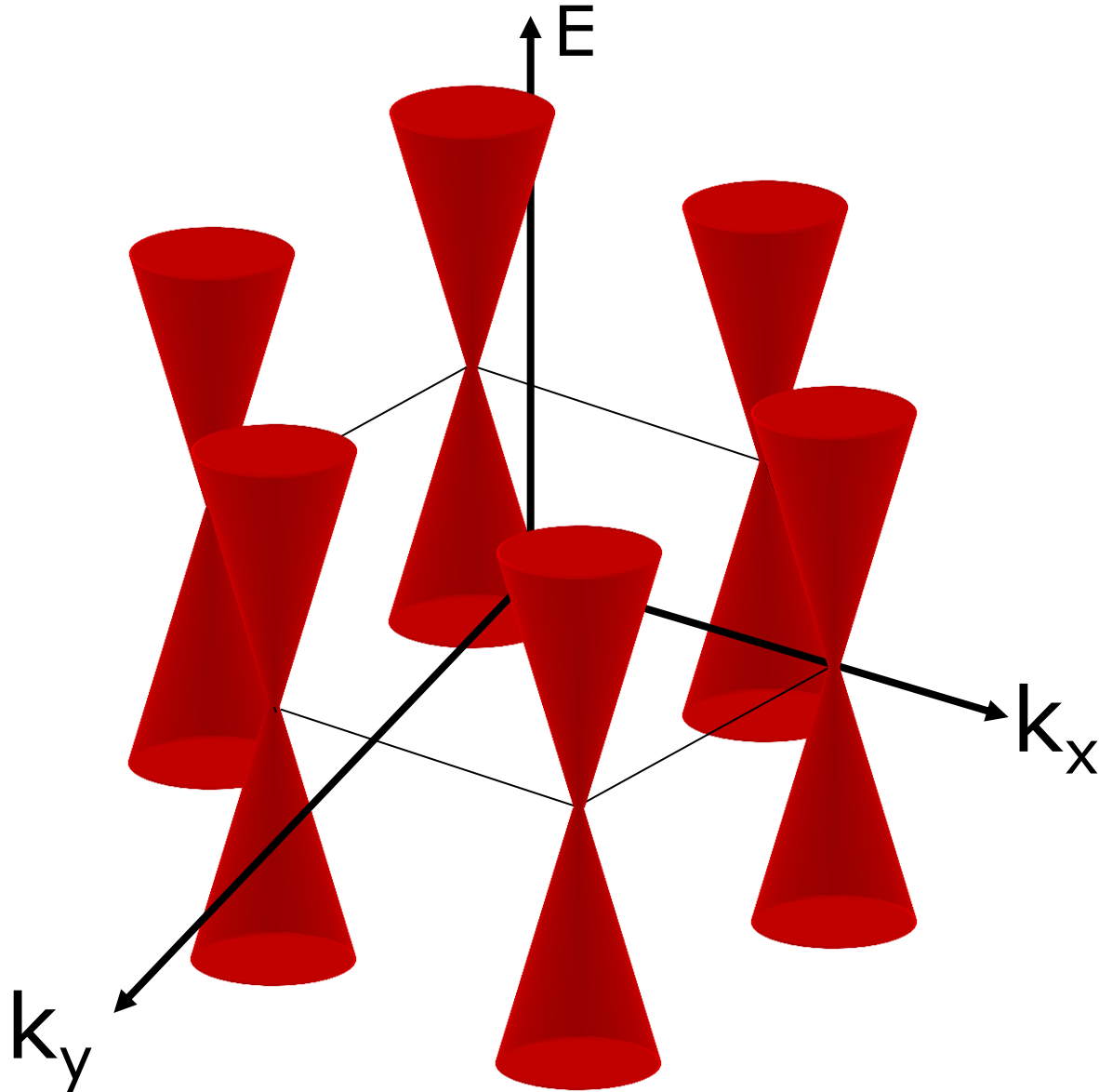
# Graphene: 2d semiconductor

---



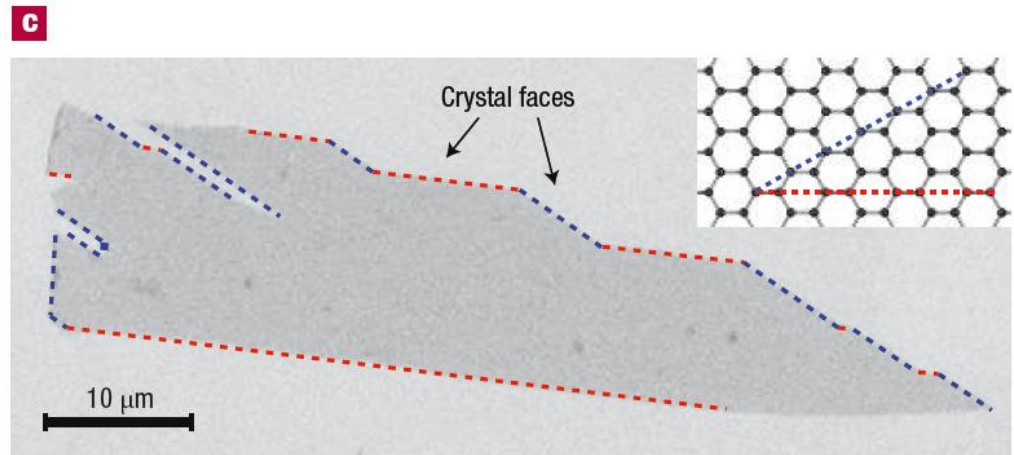
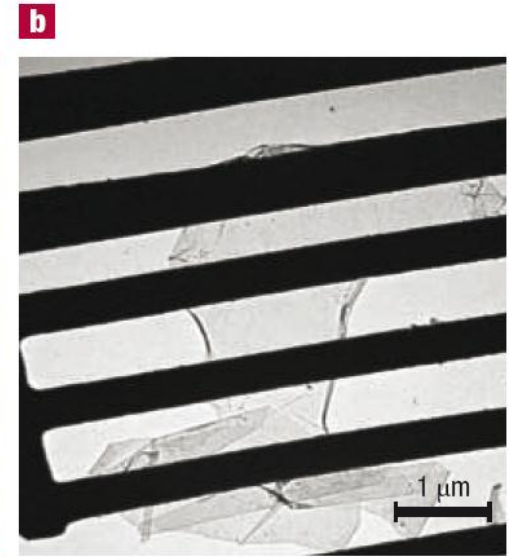
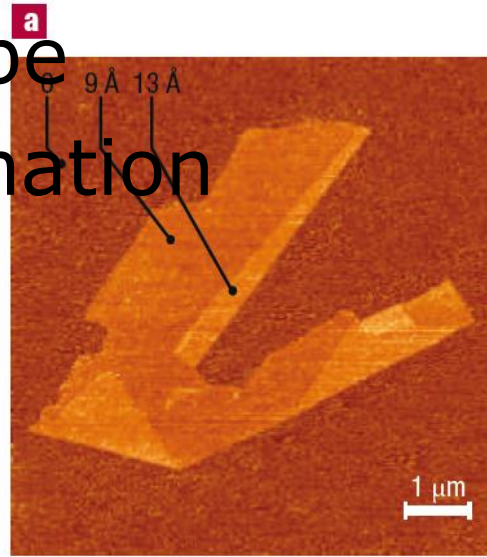
Bond length = 0.142 nm

# Graphene band structure



# Synthesis

- Scotch tape
- SiC sublimation
- CVD



A. Geim and K. Novoselov, "The Rise of Graphene", *Nature Materials*, **6**, 183-191, (2007).

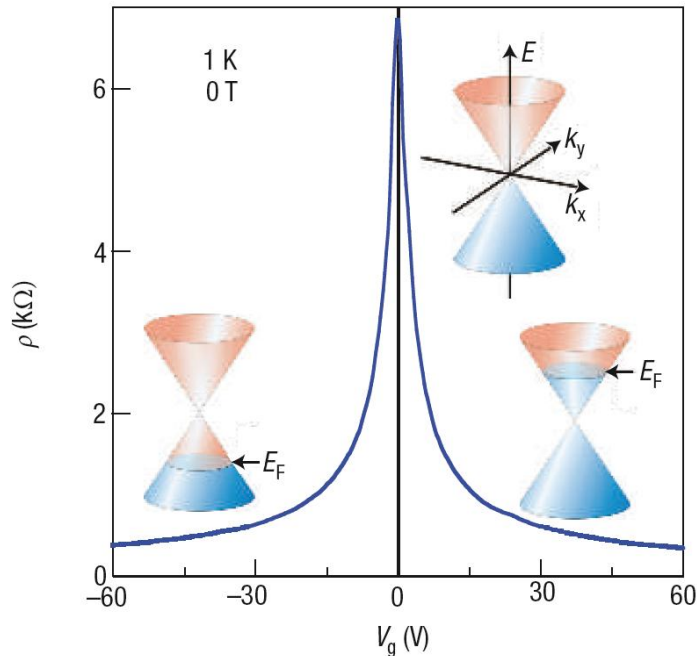
# Characterization (DJ)

---

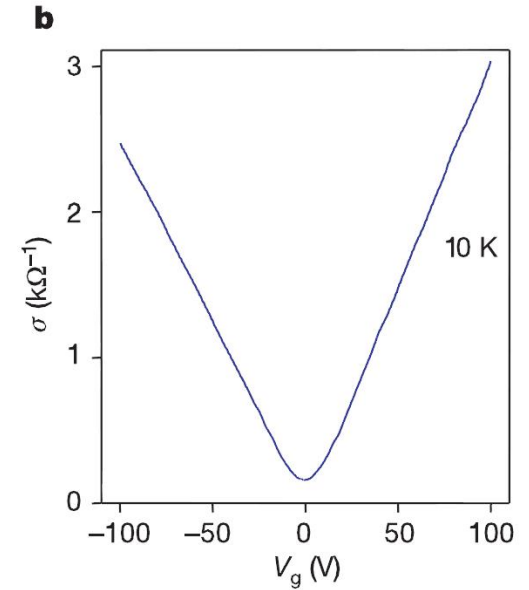
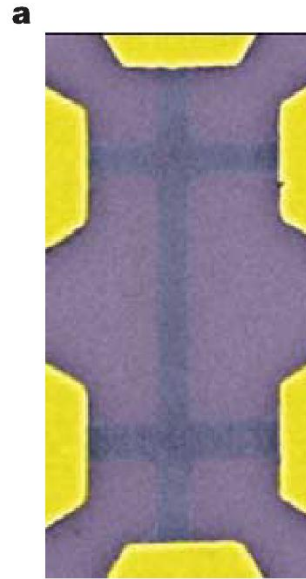
- Optical
- Raman



# Transport (back gate)

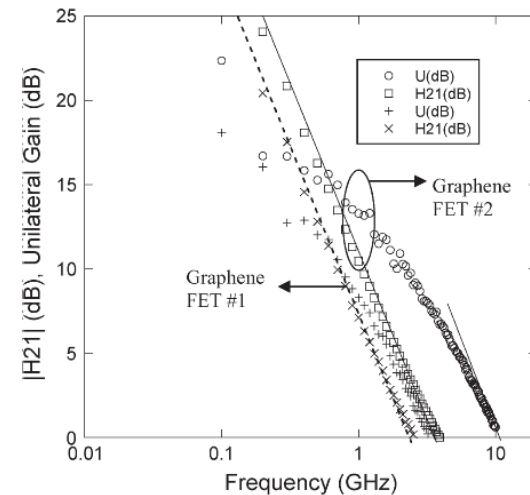
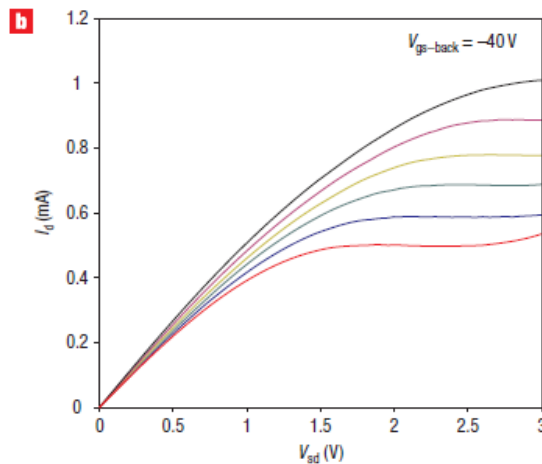
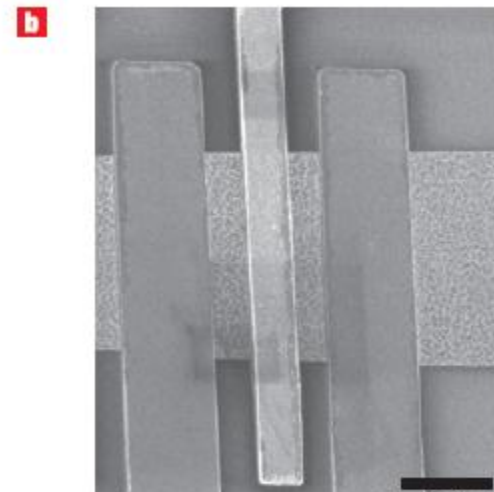
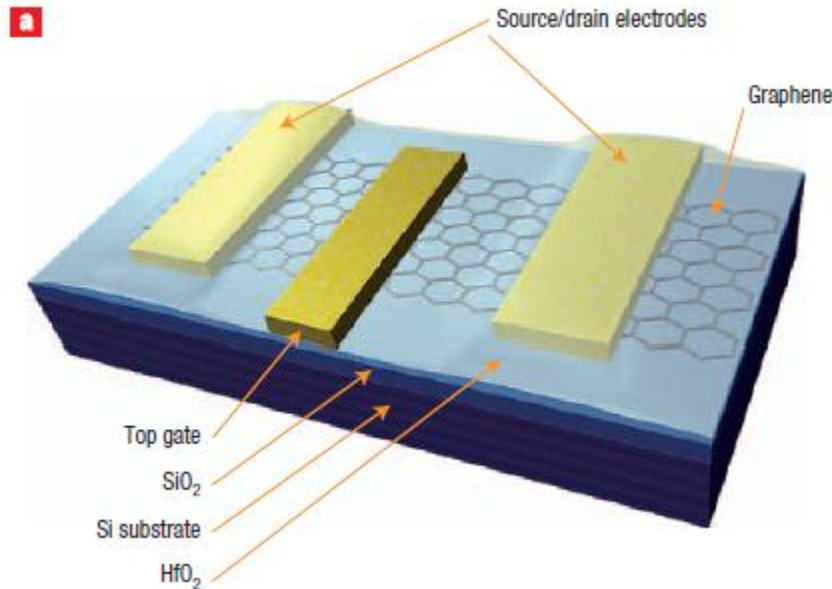


A. Geim and K. Novoselov, "The Rise of Graphene", *Nature Materials*, **6**, 183-191, (2007).



Novoselov, K., A. Geim, et al. (2005). "Two-dimensional gas of massless Dirac fermions in graphene." *Nature* **438**(7065): 197-200.

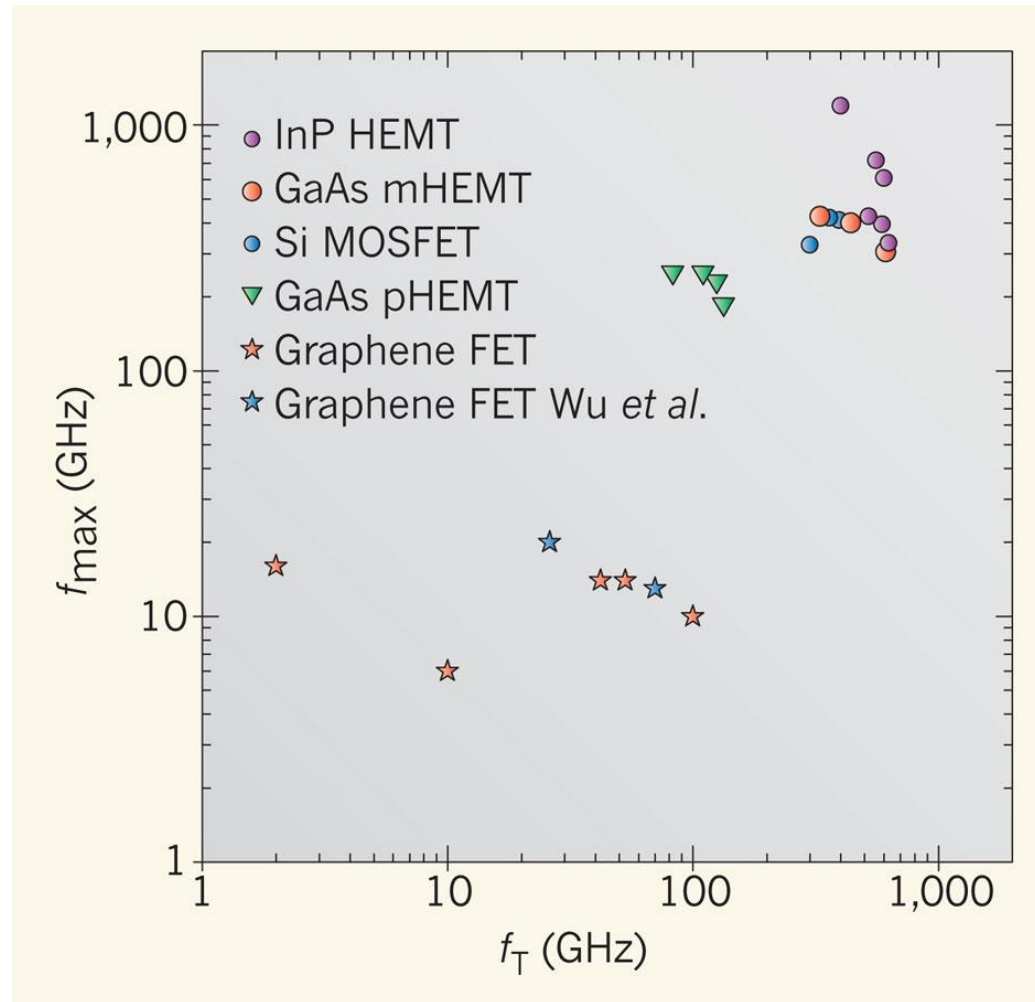
# Graphene RF FET devices



I. Meric, M. Han, A. Young, B. Ozyilmaz, P. Kim and K. Shepard, "Current Saturation in Zero-Bandgap, Top-Gated Graphene Field-Effect Transistors", *Nature Nanotechnology*, **3**, 654-659, (2008).

J. S. Moon, D. Curtis, M. Hu, D. Wong, C. McGuire, P. M. Campbell, G. Jernigan, J. L. Tedesco, B. VanMil, R. Myers-Ward, C. Eddy and D. K. Gaskill, "Epitaxial-Graphene Rf Field-Effect Transistors on Si-Face 6h-Sic Substrates", *Electron Device Letters, IEEE*, **30**, 650-652, (2009).

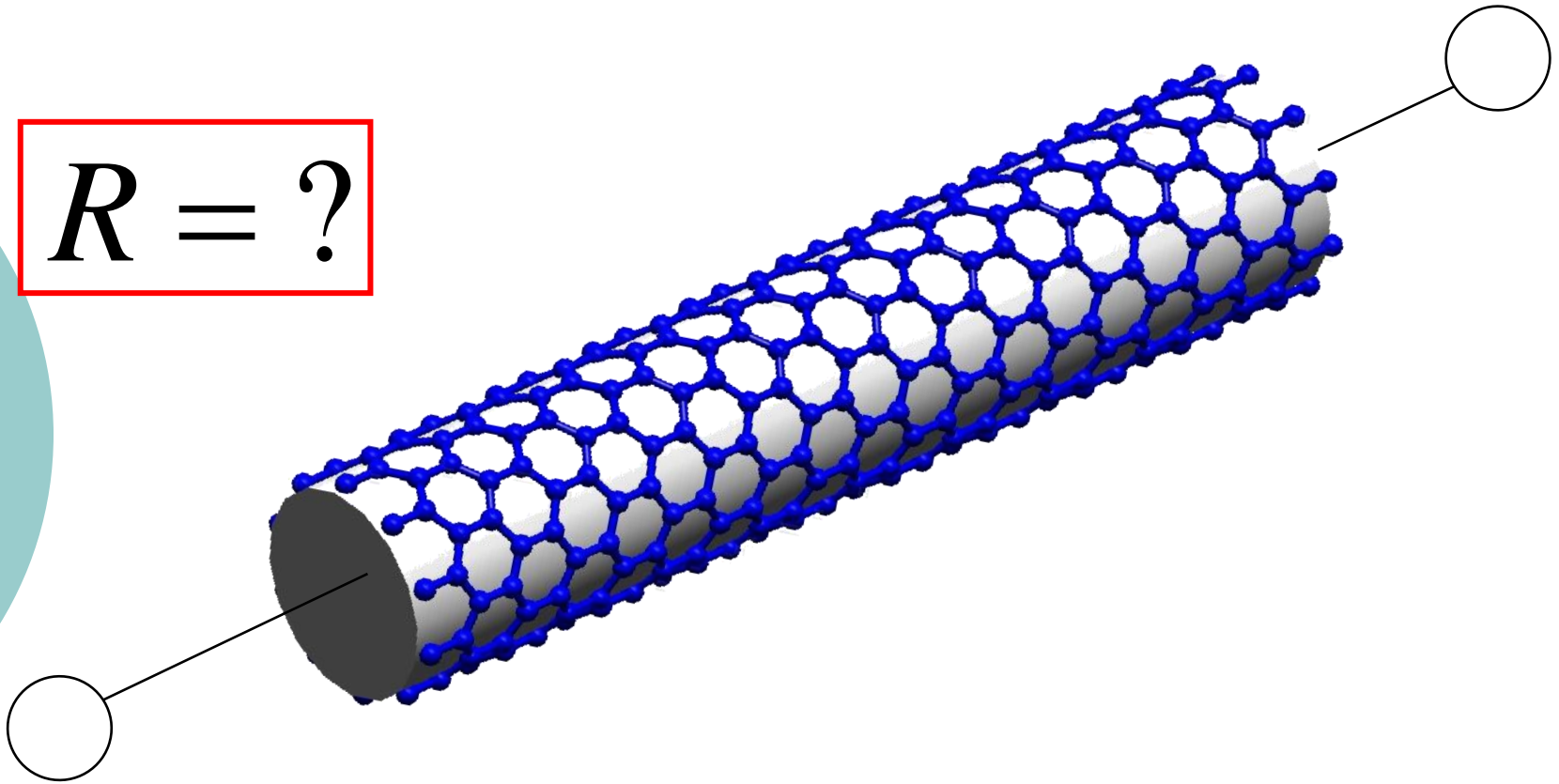
# Cutoff frequency



Schwierz, F. (2011). "Electronics: Industry-compatible graphene transistors." Nature **472**(7341): 41-42.

# Lectures 14: Carbon Nanotubes

$$R = ?$$

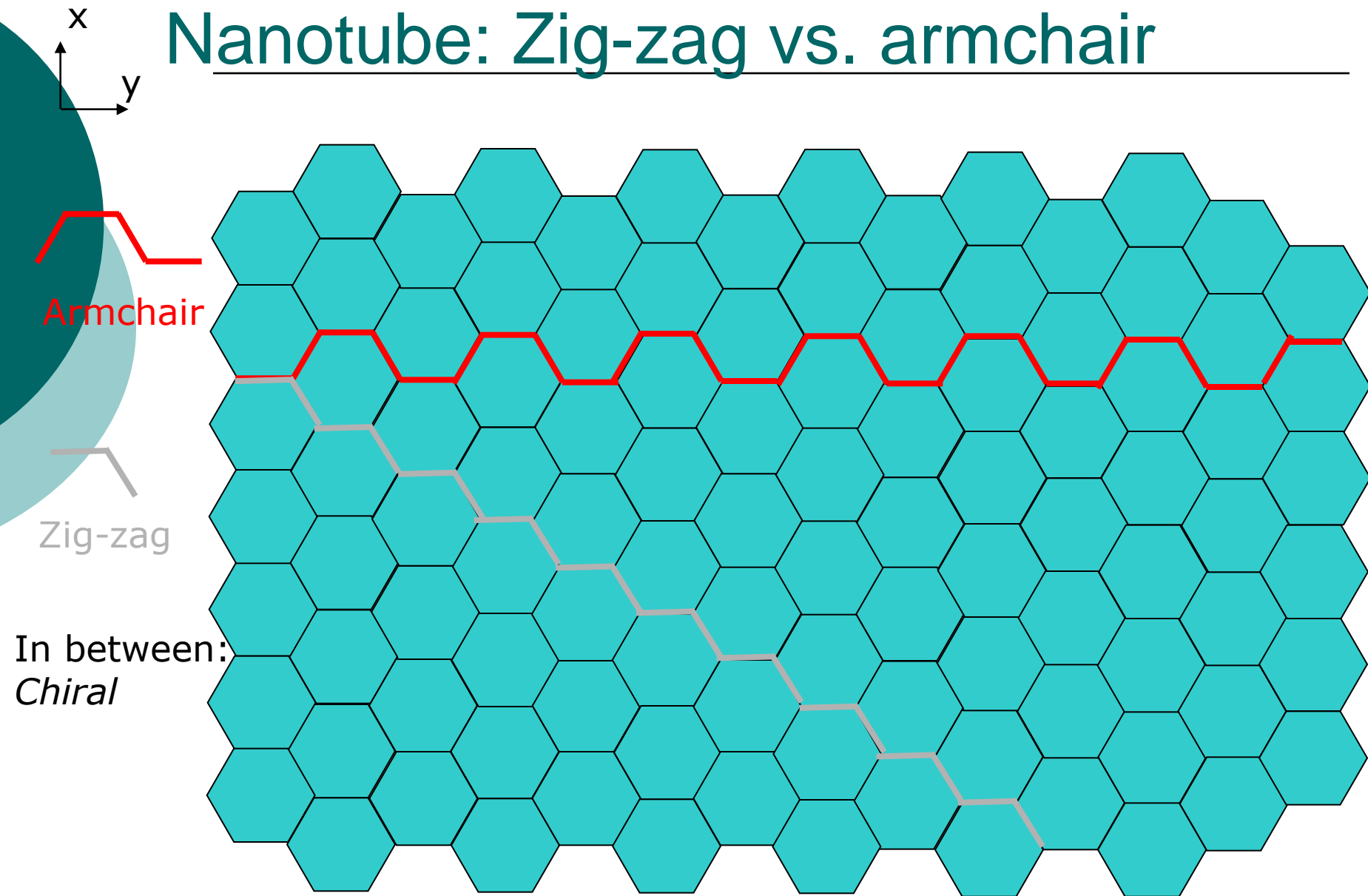


# Readings this lecture covers

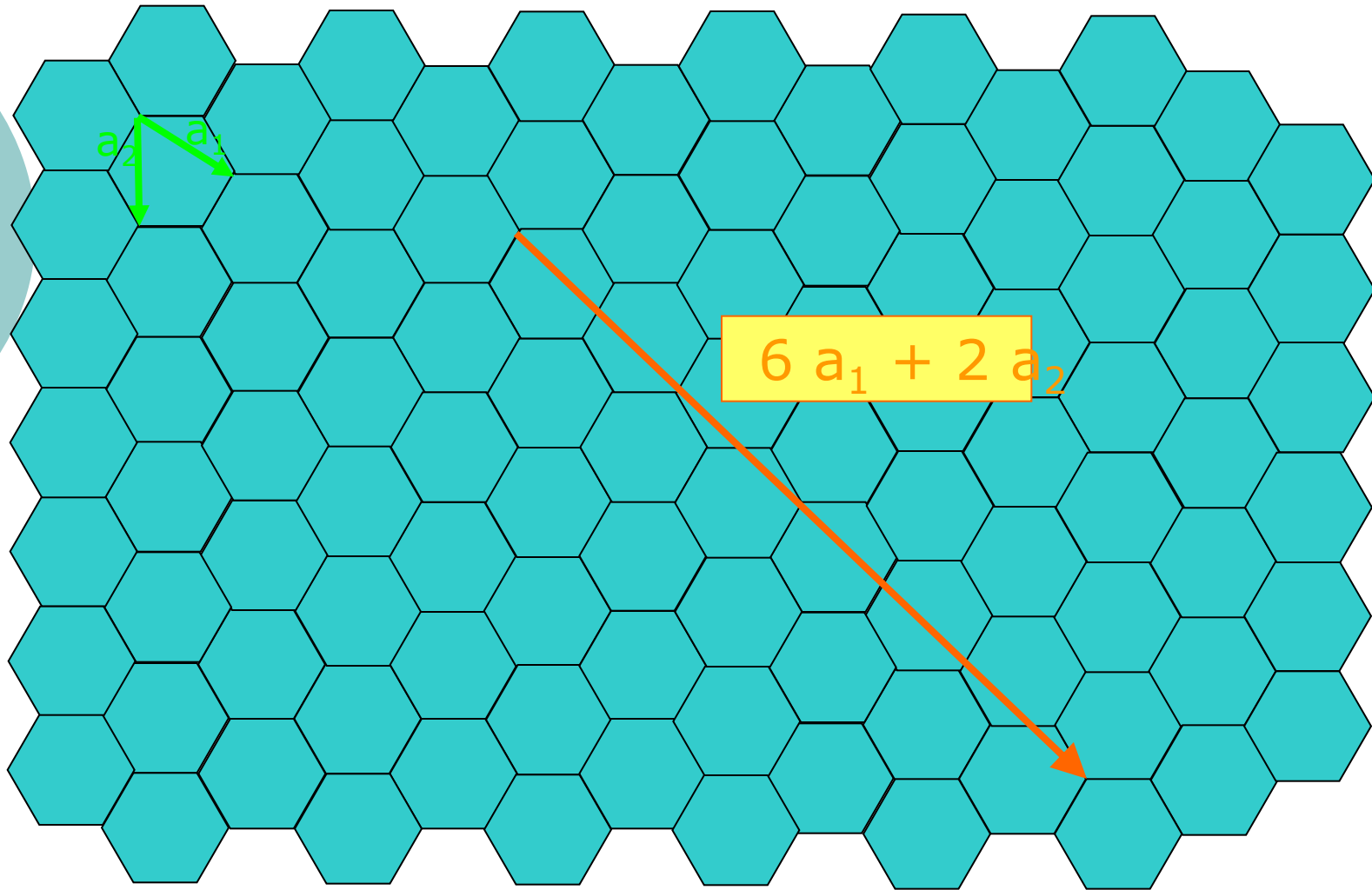
---

- Hanson, pp. 170-176
- McEuen review, *IEEE Transactions on Nanotechnology*, reading packet

# Nanotube: Zig-zag vs. armchair



# Nanotube: (n,m) description



In this example:  $(n,m) = (6,2)$

# k-vector

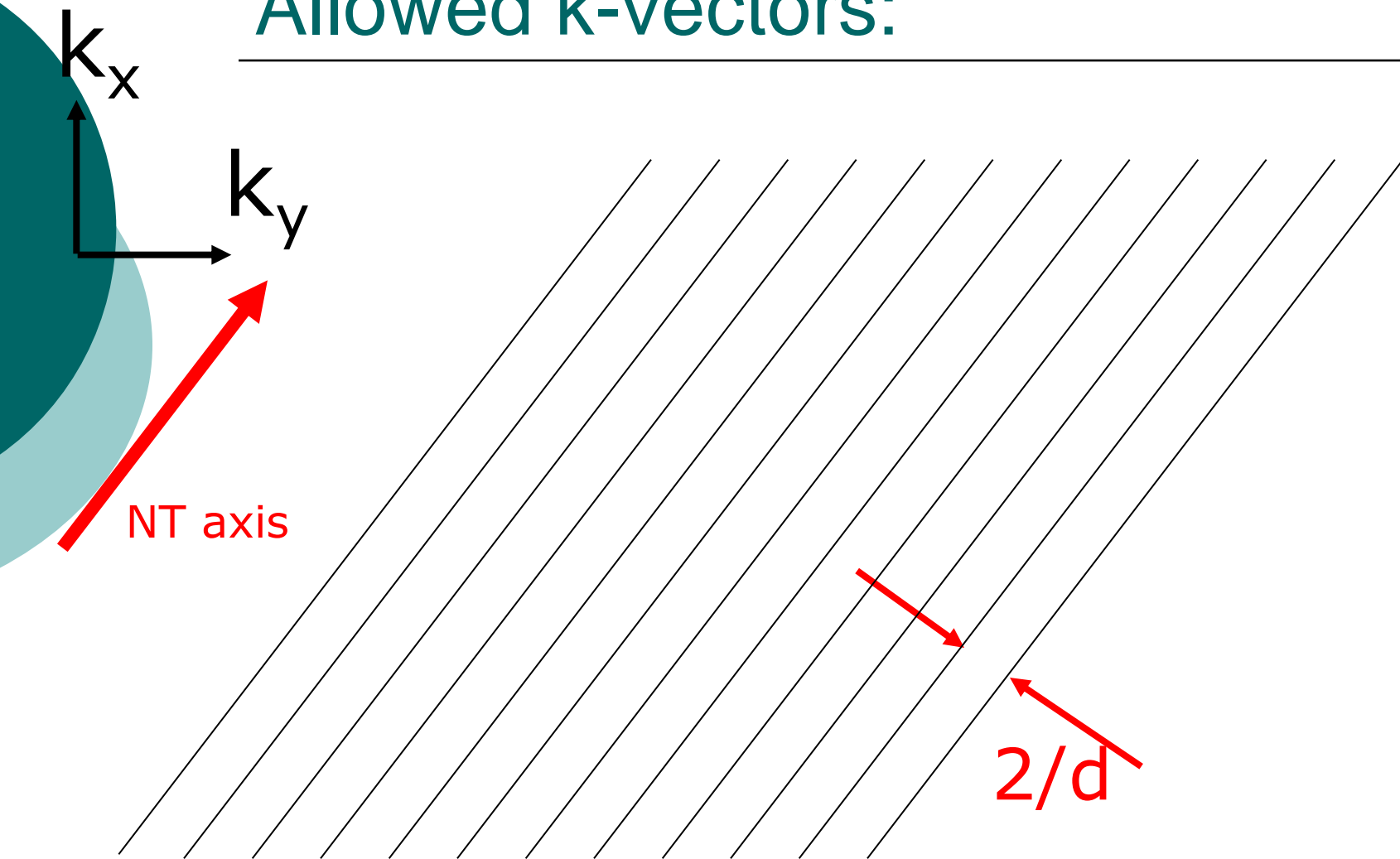
---

- Graphite:
  - Arbitrary  $k_x, k_y$  allowed
- Nanotube:
  - $\psi(\phi) = \psi(\phi + 2\pi)$
  - $k_{\text{perp}}$  spaced by  $2/d$



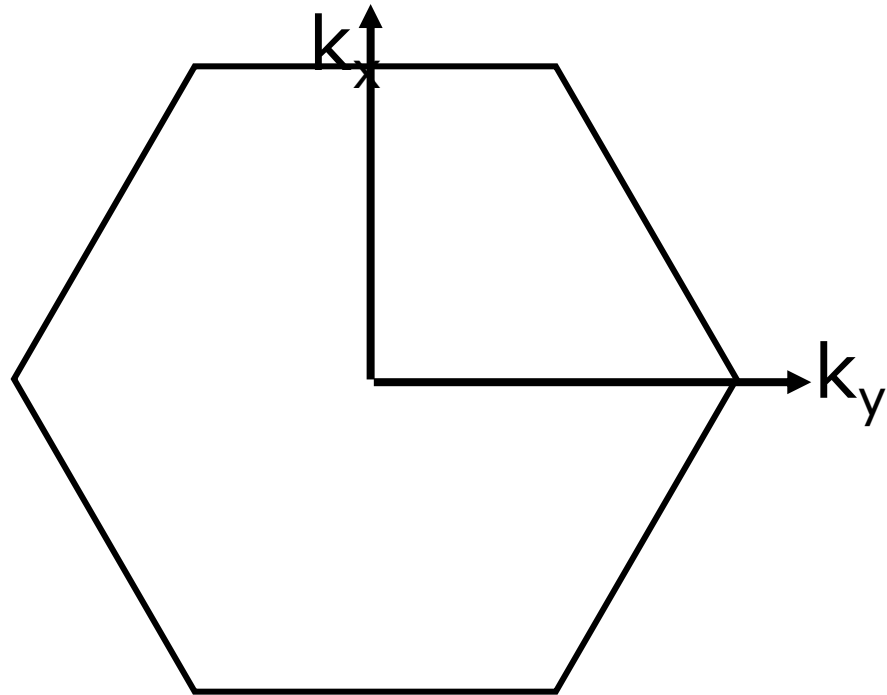
# Allowed k-vectors:

---

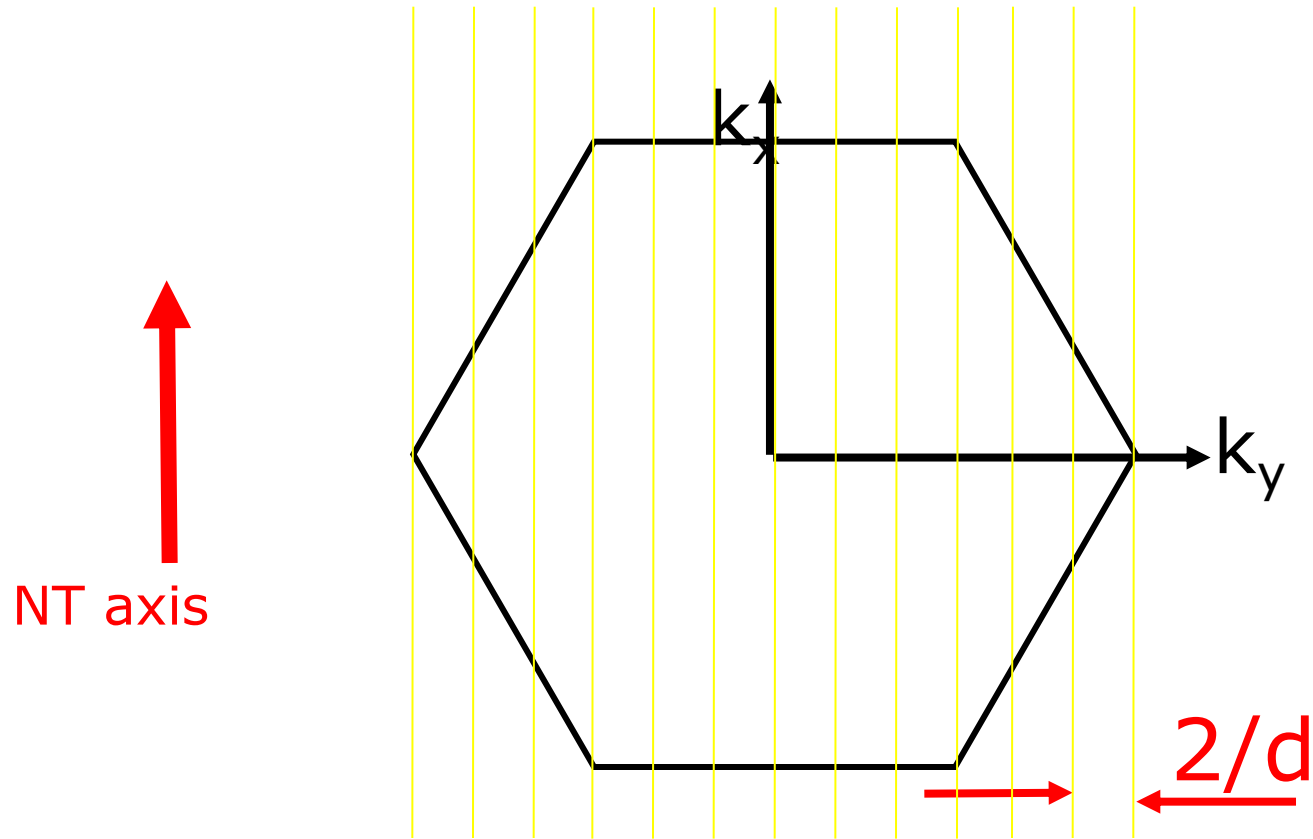


# k-space

---

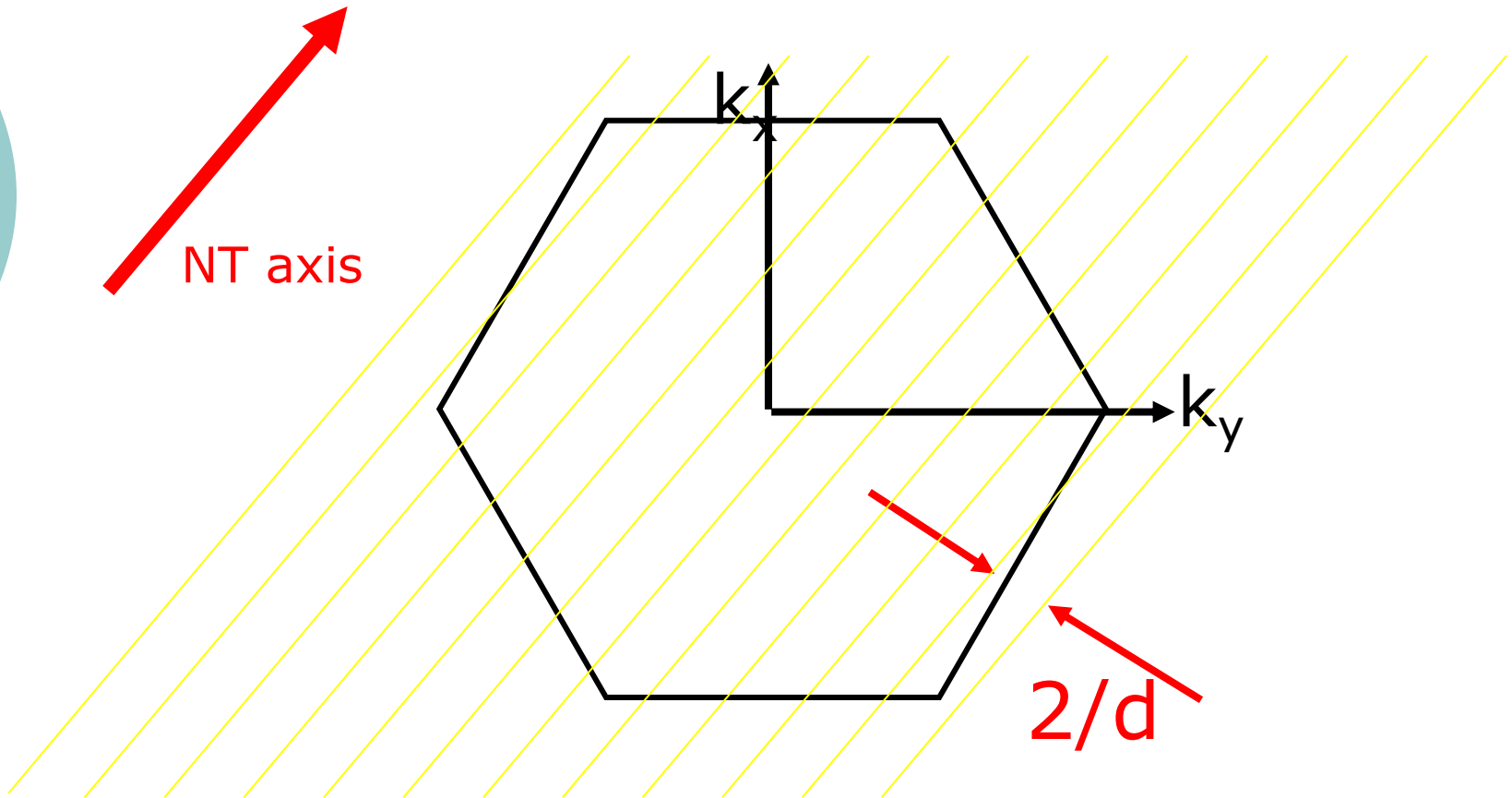


# (9,0) armchair nanotube



All armchairs are metallic.  $G = \frac{2e^2}{h} \sum T_n = \frac{4e^2}{h}$

# Semiconducting nanotube



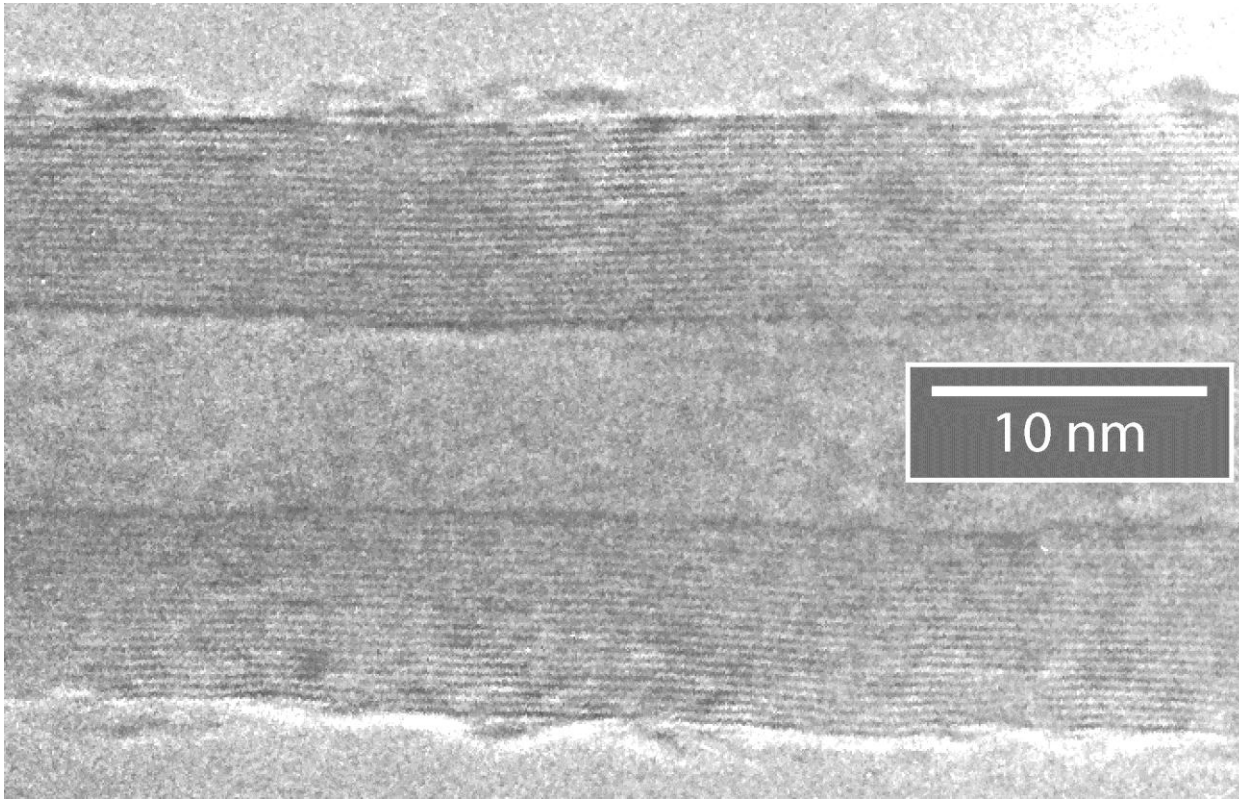
# Electrical properties

---

- All armchair metallic
- 33% of zig-zag metallic
- Semiconducting tubes:
  - Gap =  $0.9 \text{ eV}/d[\text{nm}]$

# Multi-walled nanotube (MWNT)

---



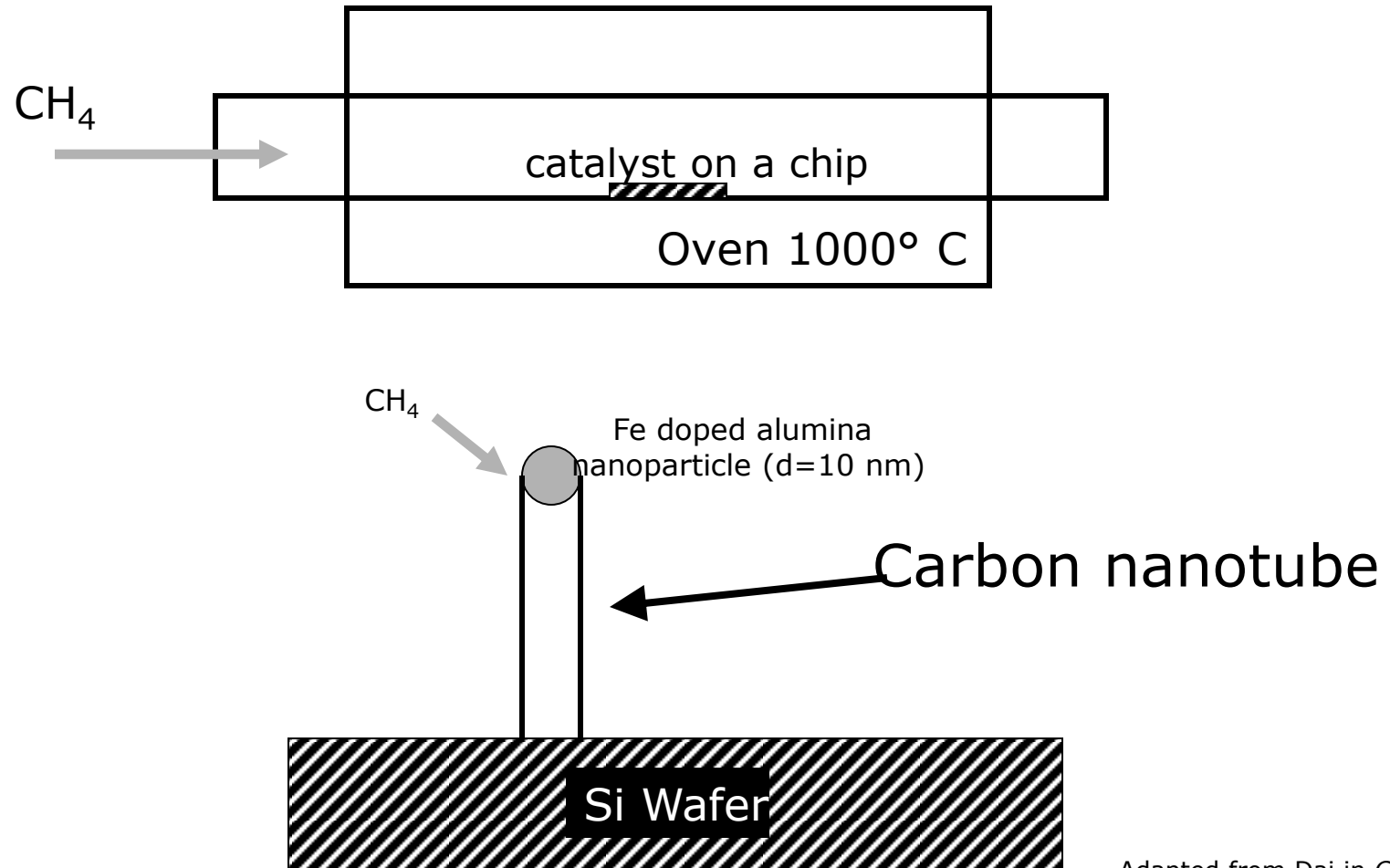
Shengdong Li, unpublished

# Growth technologies

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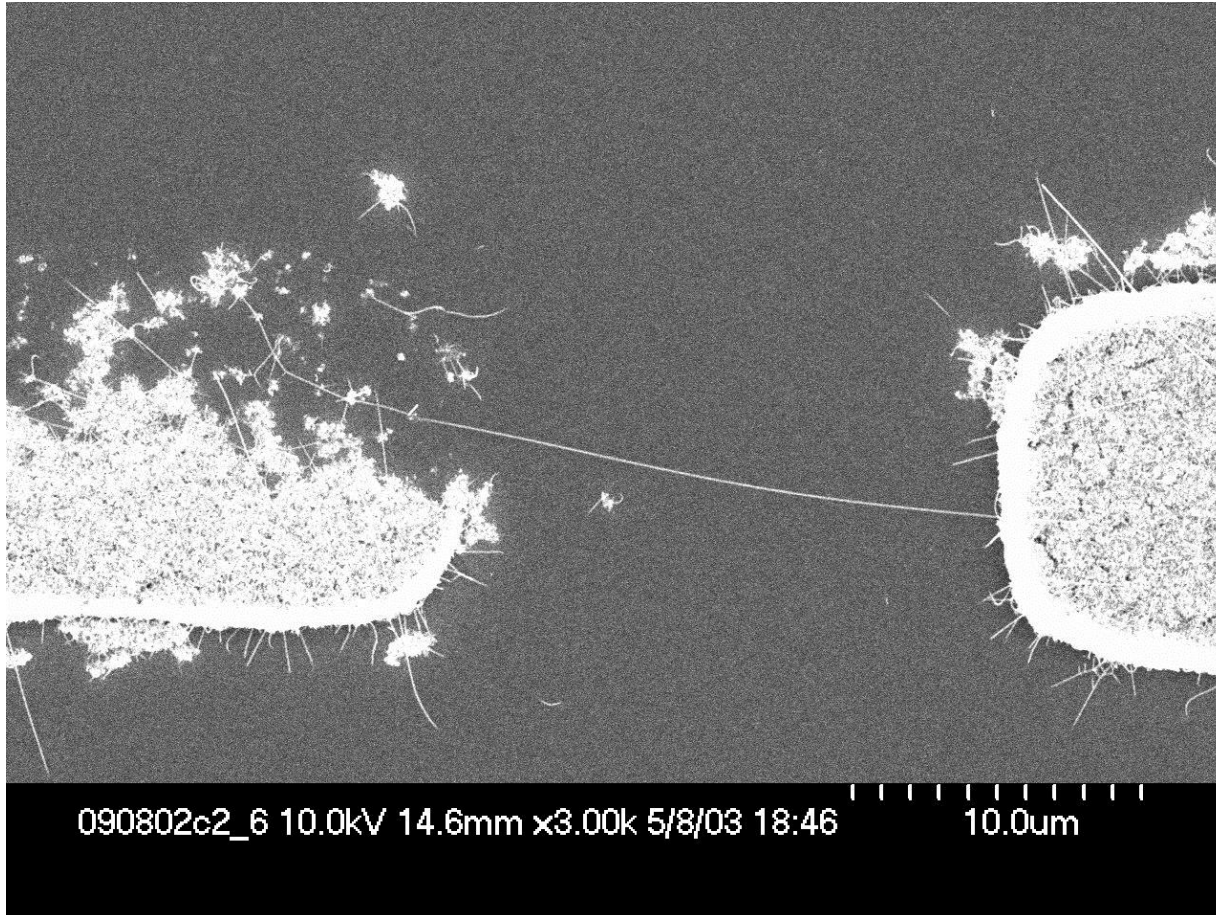
- Arc discharge
- Laser ablation
- Chemical vapor deposition (CVD)

# CVD





# Lithographically defined catalysts



Shengdong Li, unpublished

# Single Walled Carbon Nanotube

$L = 0.4 \text{ cm}$

$d/L = \text{cm/nm} = 10^7$

$d = 1.5 \text{ nm}$

Would Schelkunoff be excited?

SWNT

Au

Au

*Conductivity larger than copper!*

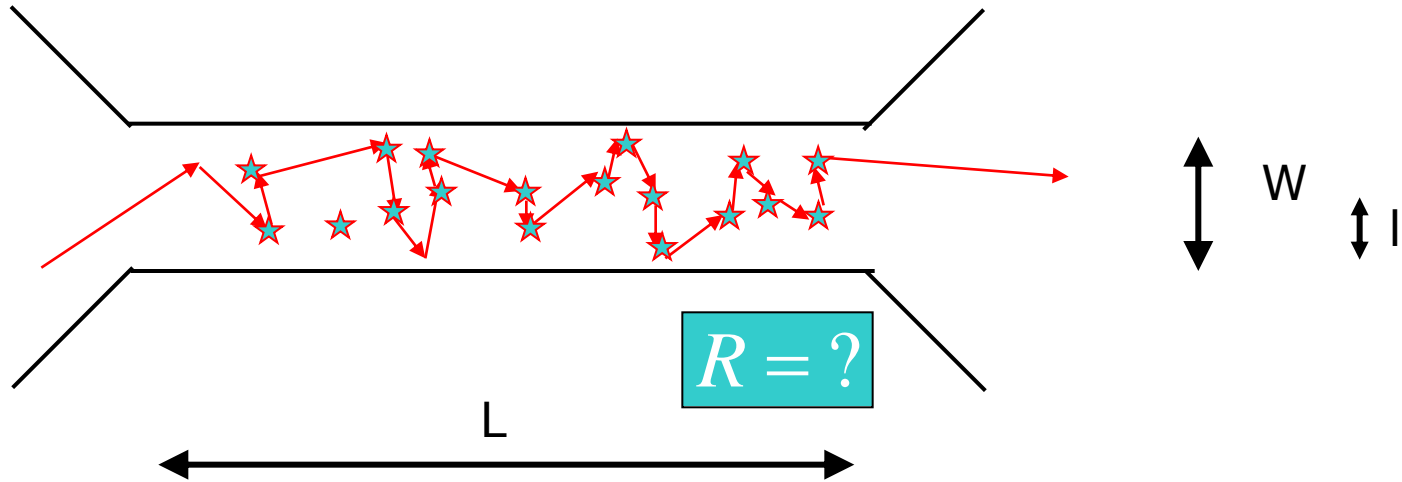
1 mm

S. D. Li, Z. Yu, C. Rutherglen and P. J. Burke, "Electrical Properties of 0.4 Cm Long Single-Walled Carbon Nanotubes", *Nano Letters*, **4**, 2003-2007, (2004).

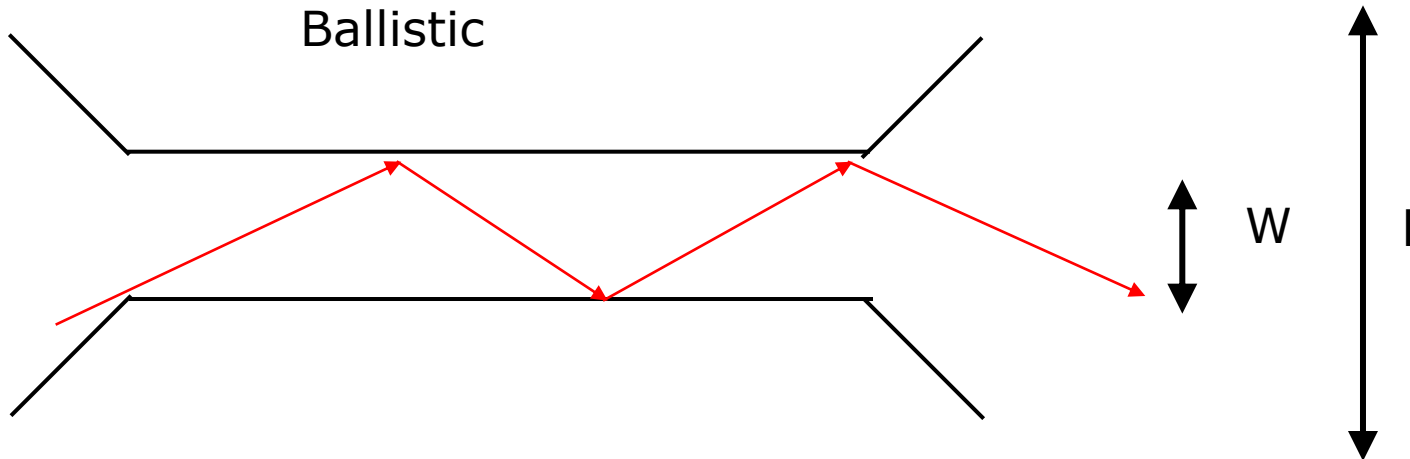
# Ballistic vs. diffusive transport

Diffusive

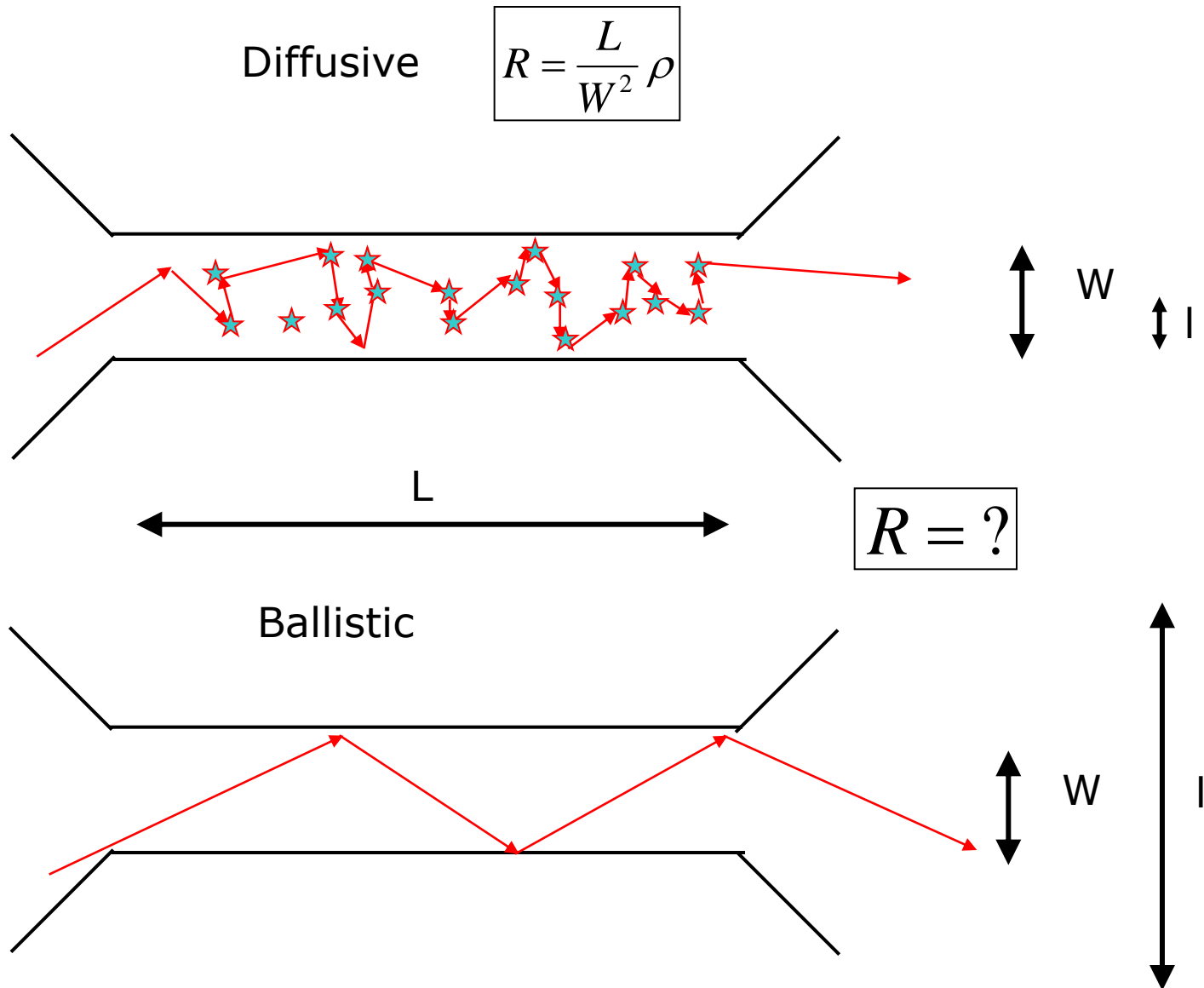
$$R = \frac{L}{W^2} \rho$$



Ballistic



# Ballistic vs. diffusive transport



# Landauer formula:

---

$$G = n \frac{2e^2}{h}$$

If the leads are not perfect injectors into each “channel” then:

$$G = \frac{2e^2}{h} \sum T_n$$

# Resistance vs. length

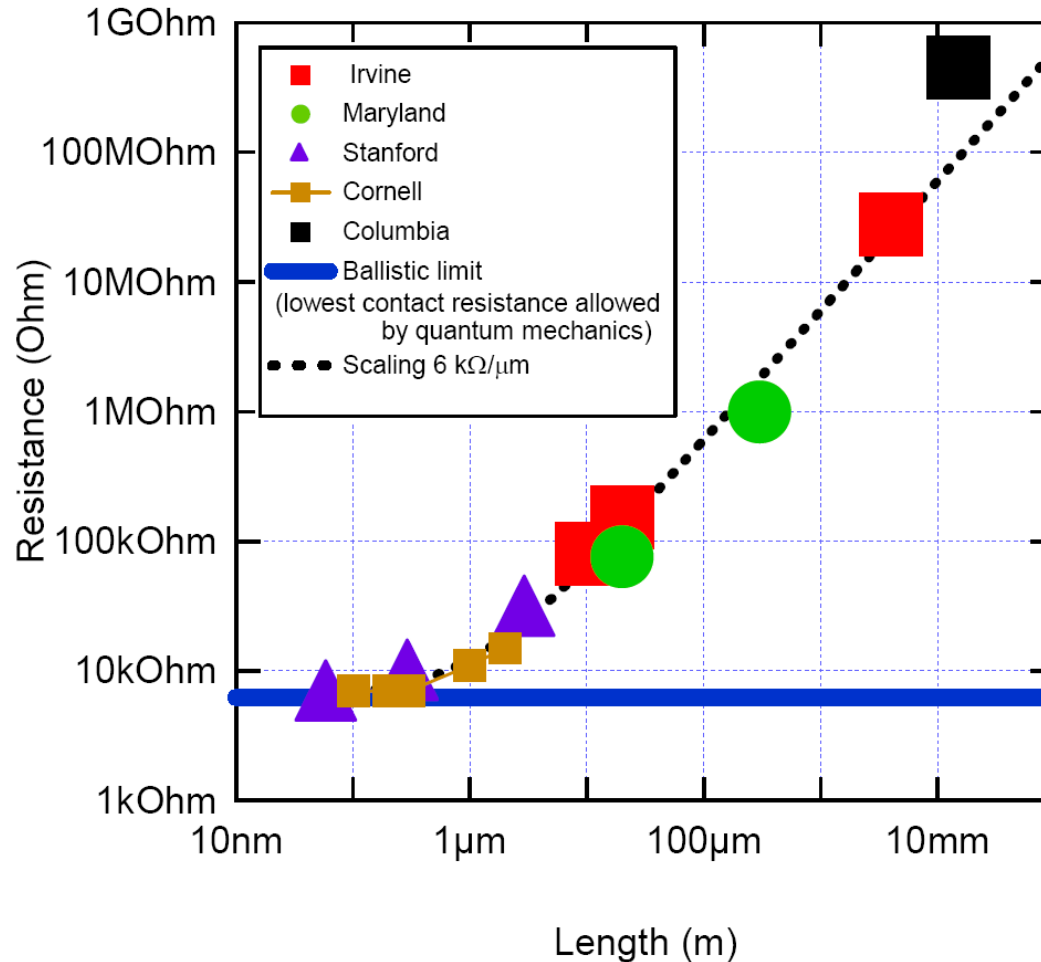
$$R(L) = R_{\text{contact}} + \frac{L}{L_{\text{mfp}}} \frac{h}{4e^2}$$

$$R_{\text{contact}} \geq h/4e^2 = 6 \text{ k}\Omega$$

Shengdong Li, Zhen Yu, C. Rutherglen, P. J. Burke "Electrical Properties of 0.4 cm Long Single-Walled Carbon Nanotubes", *Nano Letters*, 2004.

# Resistance vs. length

$$R = R_{\text{contact}} + L \cdot 6 \text{ k}\Omega/\mu\text{m}$$



Shengdong Li, Zhen Yu, C. Rutherglen, P. J. Burke "Electrical Properties of 0.4 cm Long Single-Walled Carbon Nanotubes", *Nano Letters*, 2004.

# R vs L single tube

PRL 98, 186808 (2007)

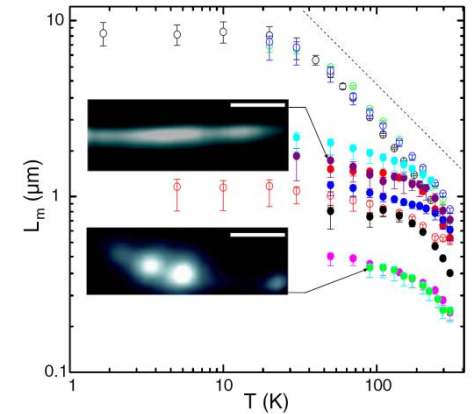
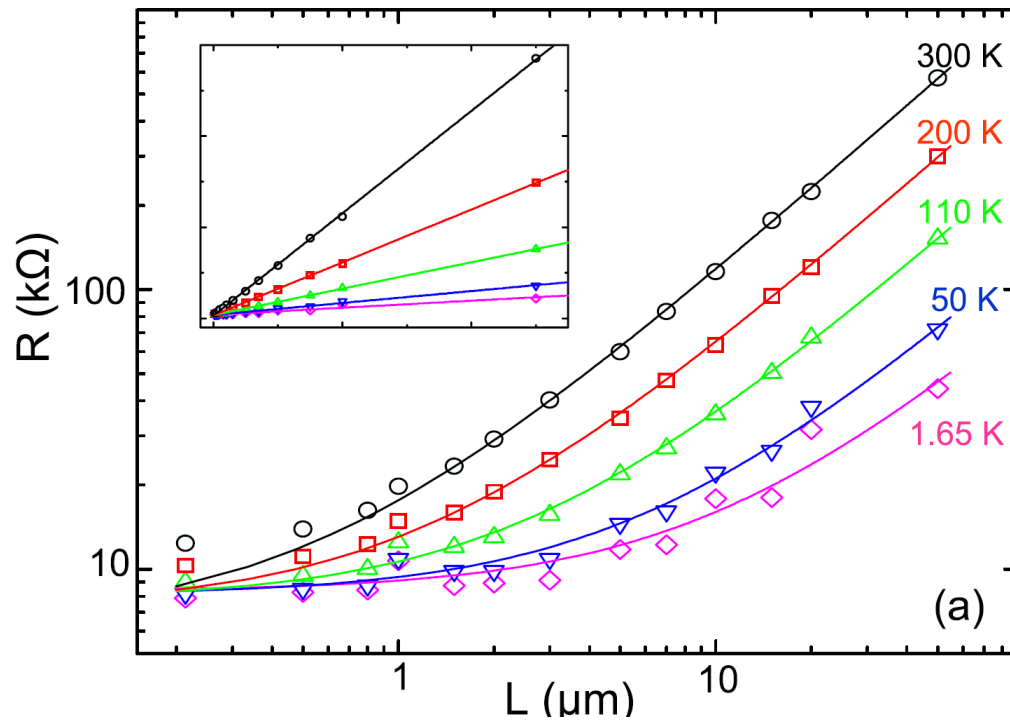
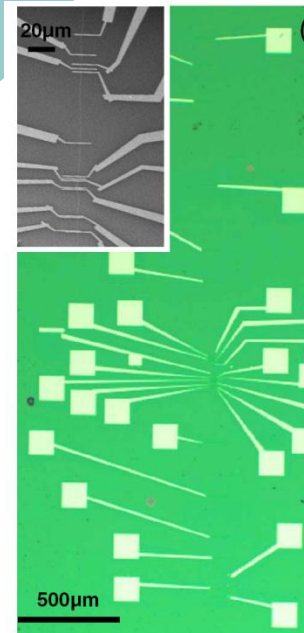
PHYSICAL REVIEW LETTERS

week ending  
4 MAY 2007



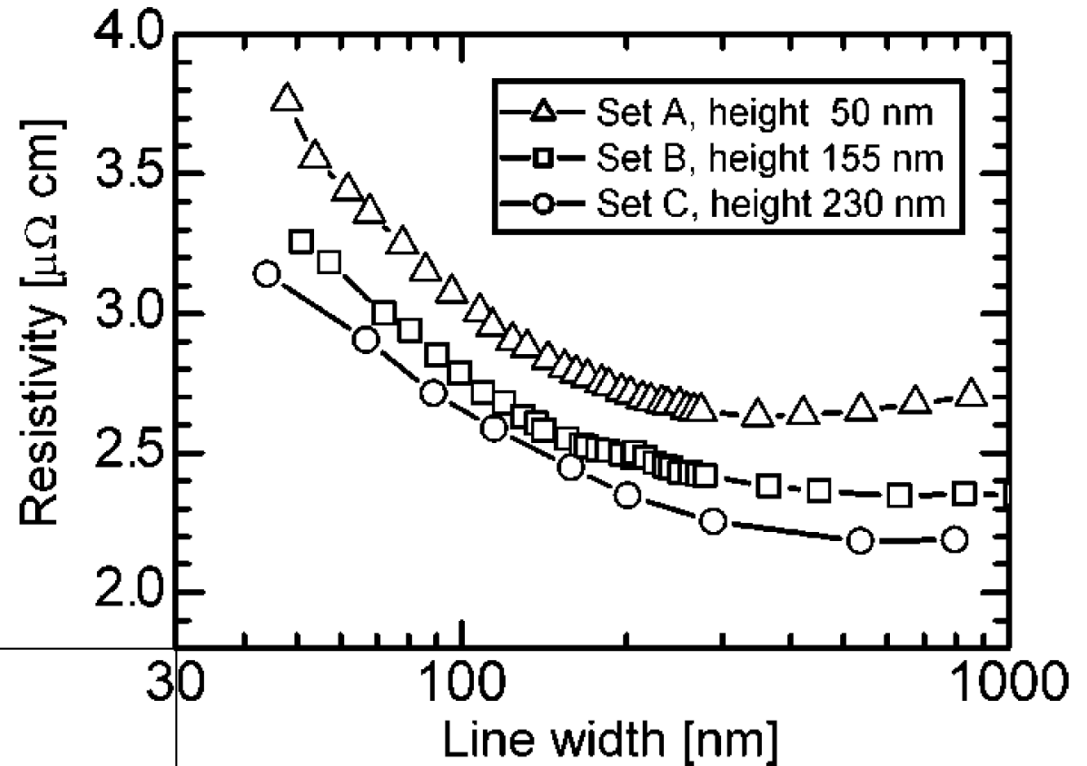
## Scaling of Resistance and Electron Mean Free Path of Single-Walled Carbon Nanotubes

Meninder S. Purewal,<sup>1</sup> Byung Hee Hong,<sup>2</sup> Anirudhh Ravi,<sup>2</sup> Bhupesh Chandra,<sup>3</sup> James Hone,<sup>3</sup> and Philip Kim<sup>2</sup>





# Comparison to Cu



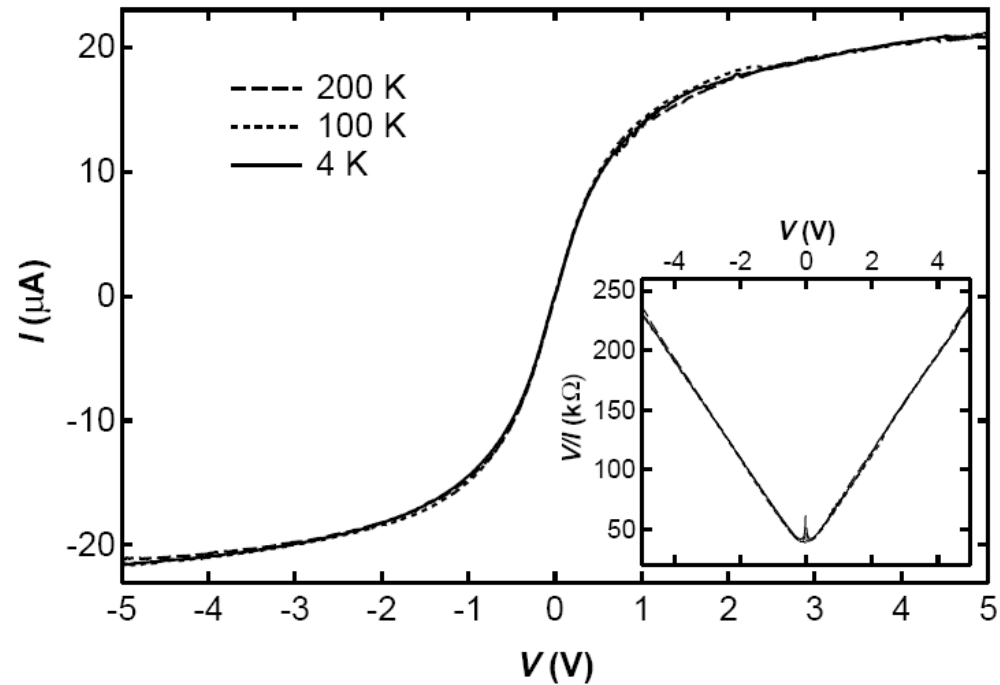
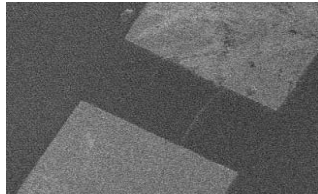
**SWNT**



$d=1.5\text{ nm}$ ,  $6\text{ k}\Omega/\mu\text{m}$   
 $\Rightarrow 1.1\ \mu\Omega\text{-cm}$

[1.] W. Steinhogel, G. Schindler, G. Steinlesberger, M. Traving and M. Engelhardt, "Comprehensive Study of the Resistivity of Copper Wires with Lateral Dimensions of 100 Nm and Smaller", *Journal of Applied Physics*, **97**, 023706, (2005).

# High field transport. Diffusive regime



Prior dc work:

High-Field Electrical Transport in Single-Wall Carbon Nanotubes

$$V/I = R_0 + |V|/I_0$$

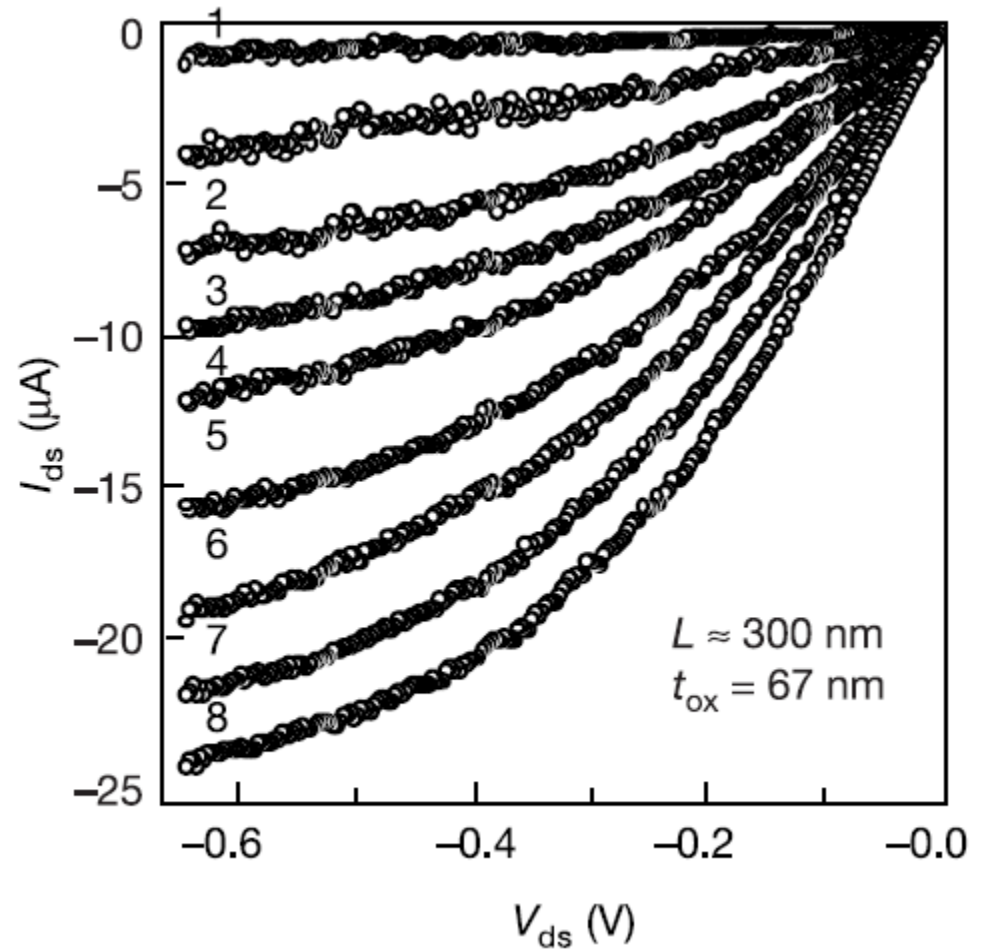
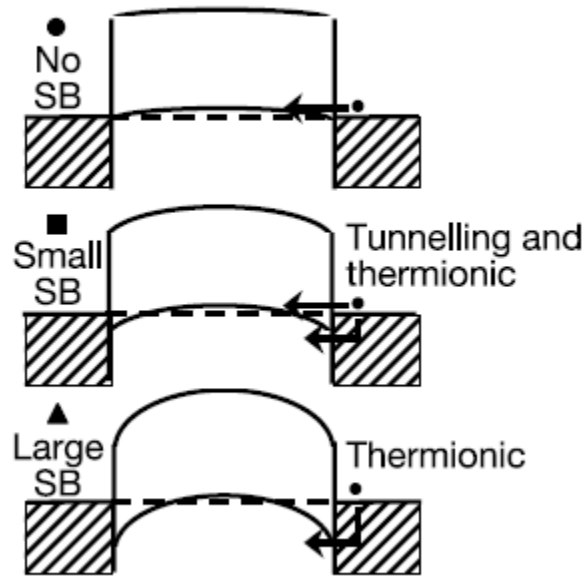
[Zhen Yao](#)<sup>1</sup>, [Charles L. Kane](#)<sup>2</sup>, and [Cees Dekker](#)<sup>1</sup>

Phys. Rev. Lett. 84, 2941 - 2944 (2000)

[Issue 13 - March 2000]



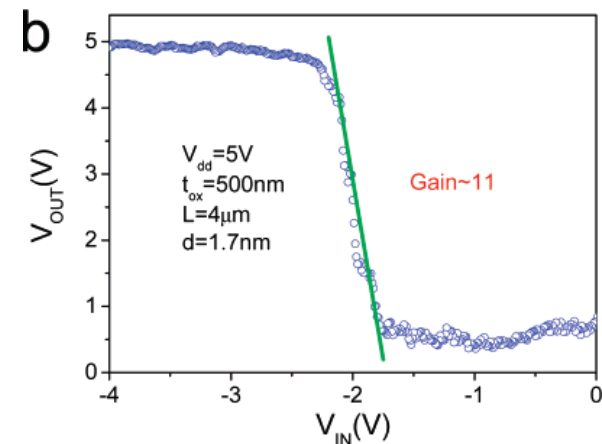
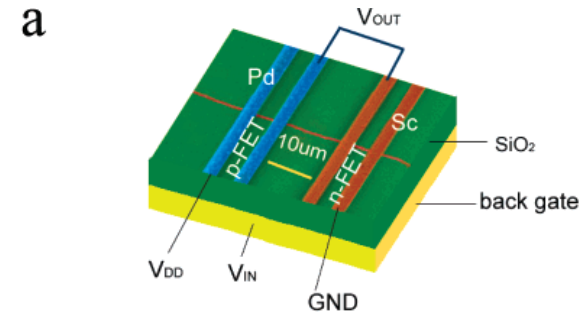
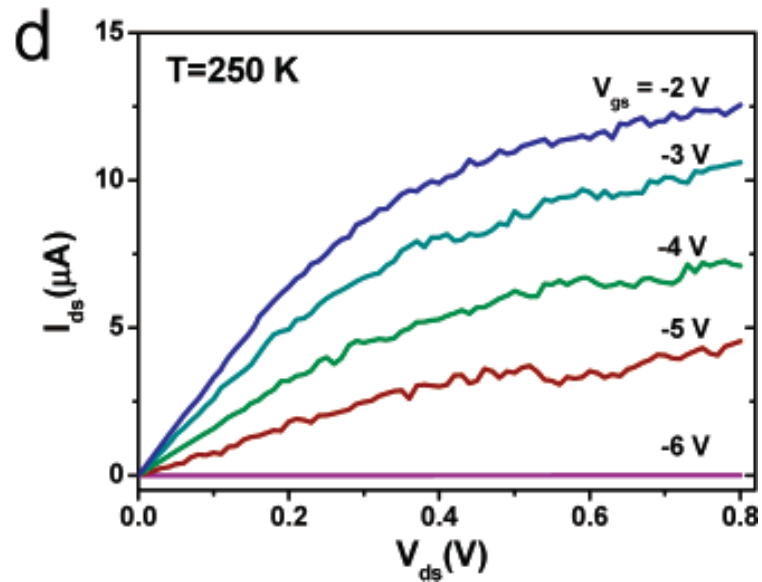
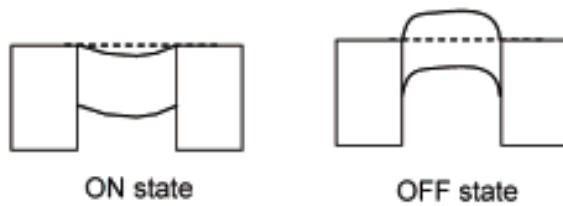
# Ohmic p-type contact



Ballistic carbon nanotube field-effect transistors

Ali Javey Jing Guo Qian Wang Mark Lundstrom & Hongjie Dai  
Nature 424, 654 - 657 (2003).

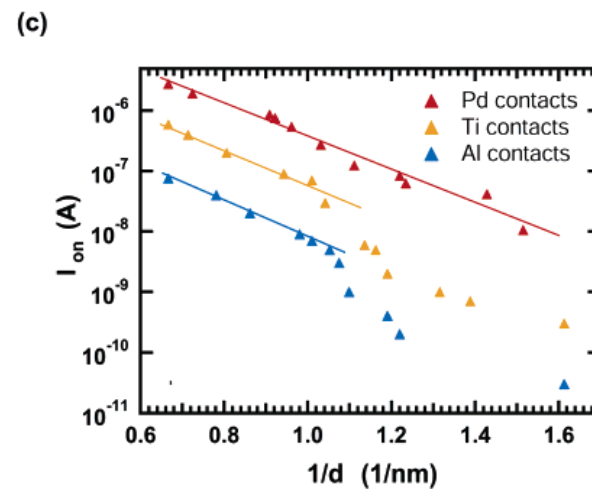
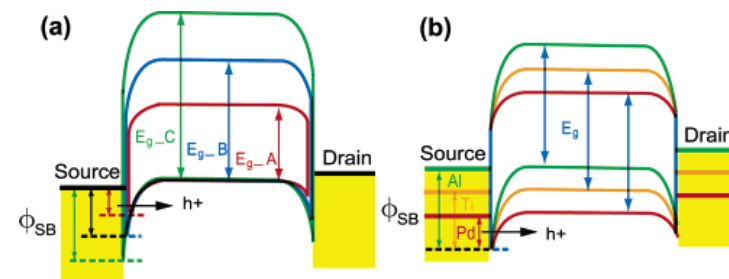
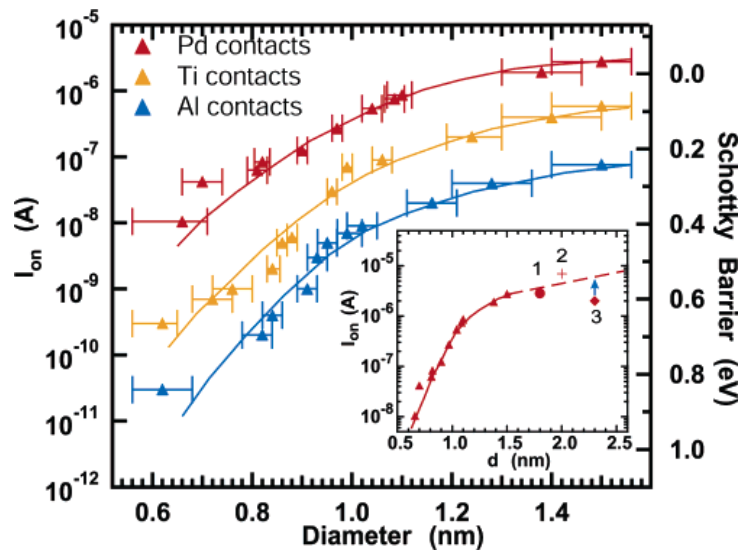
# Ohmic n-type contact



Doping-Free Fabrication of Carbon Nanotube Based Ballistic CMOS Devices and Circuits

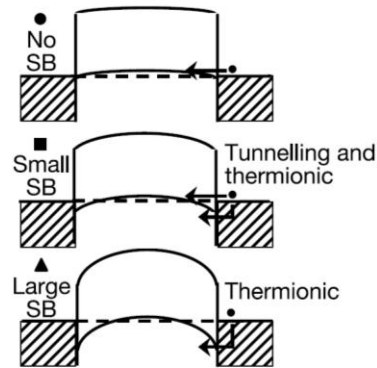
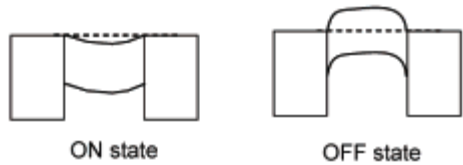
Zhang, Z.; Liang, X.; Wang, S.; Yao, K.; Hu, Y.; Zhu, Y.; Chen, Q.; Zhou, W.; Li, Y.; Yao, Y.; Zhang, J.; Peng, L.-  
Nano Lett.; (Letter); 2007; 7(12); 3603-3607

# Electrical contact: Role of metals



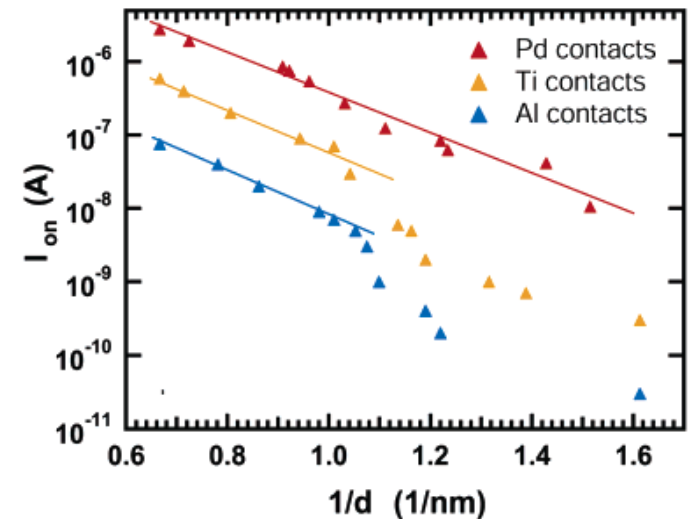
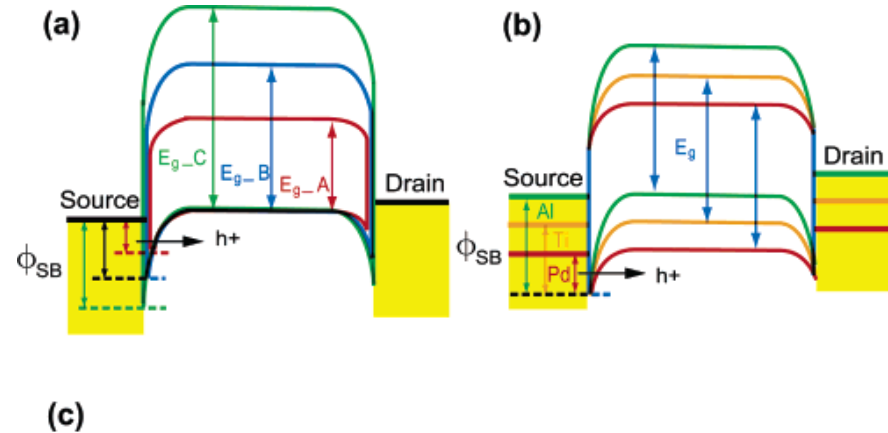
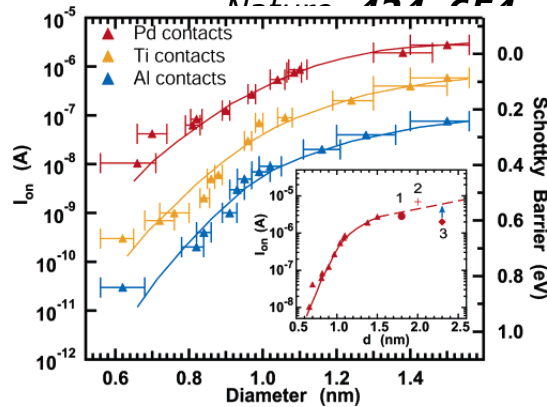
The Role of Metal-Nanotube Contact in the Performance of Carbon Nanotube Field-Effect Transistors  
 Chen, Z.; Appenzeller, J.; Knoch, J.; Lin, Y.-M.; Avouris, Ph.  
 Nano Lett.; (Letter); 2005; 5(7); 1497-1502.

# N-type, p-type, SB FET



X. Peng, N. Komatsu, S. Bhattacharya, T. Shimawaki, S. Aonuma, T. Kimura and A. Osuka, "Optically Active Single-Walled Carbon Nanotubes", *Nature*, **2**, **361-365**, (2007).

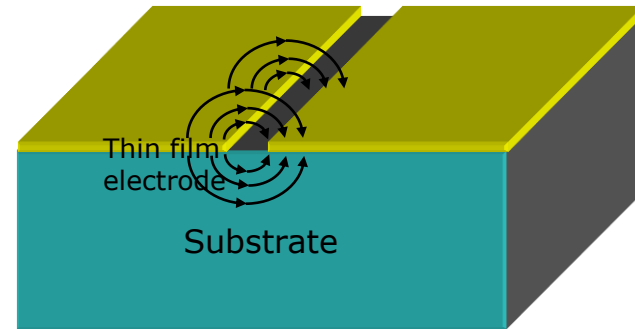
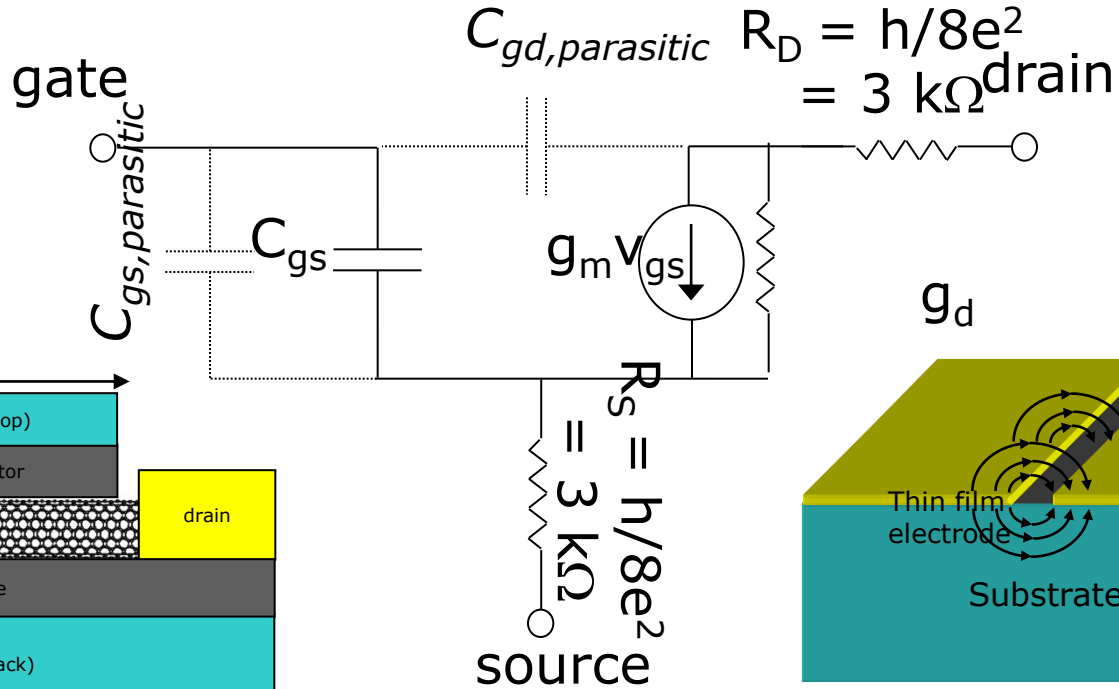
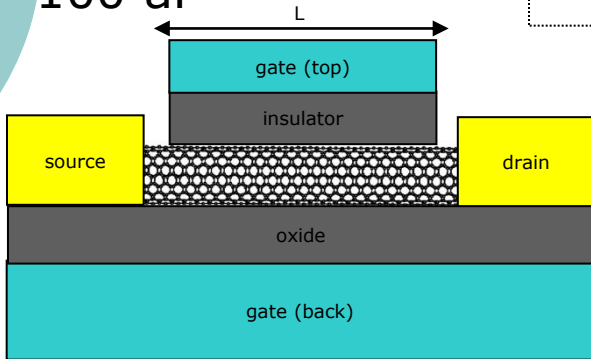
A. Javey, J. Guo, Q. Wang, M. Lundstrom and H. J. Dai, "Ballistic Carbon Nanotube Field-Effect Transistors", *Nature*, **424**, **654**, (2002).



Z. Chen, J. Appenzeller, J. Knoch, Y.-M. Lin and P. Avouris, "The Role of Metal-Nanotube Contact in the Performance of Carbon Nanotube Field-Effect Transistors", *Nano Lett.*, **5**, **1497-1502**, (2005).

# Effect of parasitics

$C_{gs} \sim 1-10 \text{ aF}$   
 $g_m \sim 10 \mu\text{S}$   
 $C_p \sim 100 \text{ aF}$



If parasitics minimized:

$$\frac{1}{2\pi f_T} = (R_S + R_D)C_{gd,p} + \frac{1}{g_m}(C_{gs} + C_{gd,p} + C_{gd,p}) + \frac{g_d}{g_m}(R_S + R_D)(C_{gs} + C_{gd,p} + C_{gd,p})$$

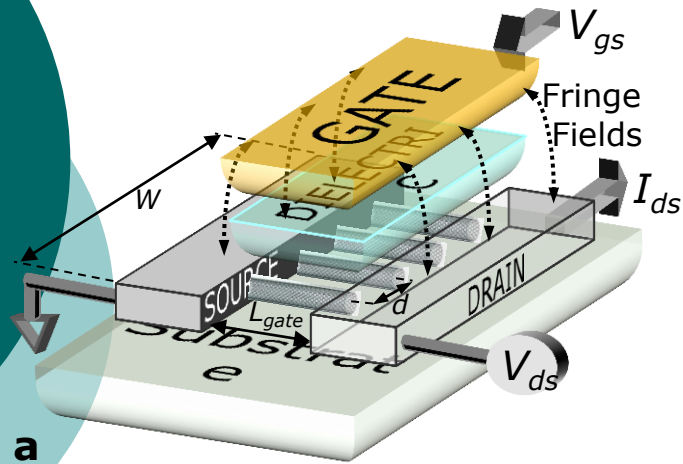
$\sim 10 \text{ GHz}$

$$\frac{1}{2\pi f_T} = \frac{C_{gs}}{g_m}$$

$\sim 1 \text{ THz}$

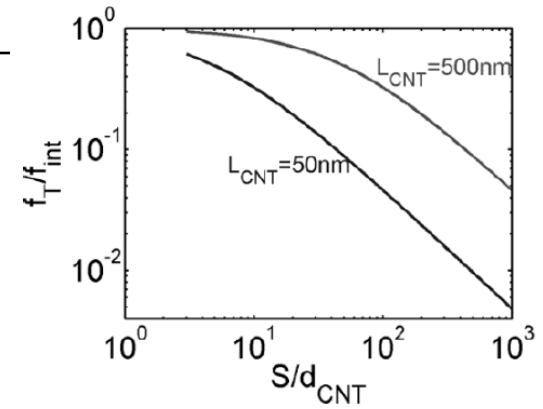


# Nanotube density



$$f_T = \frac{g_m}{2\pi C_{gs}}$$

$$f_T = \frac{g_m}{2\pi C_{gs}} \left( \frac{1}{1 + \frac{C_w}{C_{gs}} d} \right)$$



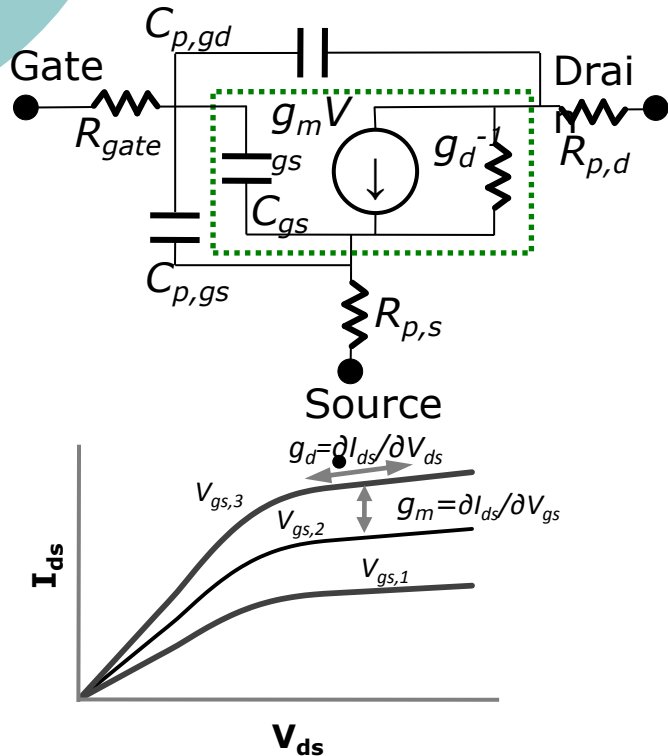
J. Guo, S. Hasan, A. Javey, G. Bosman and M. Lundstrom, "Assessment of High-Frequency Performance Potential of Carbon Nanotube Transistors", *IEEE Transactions on Nanotechnology*, **4**, 715-721, (2005).

C. Rutherglen, D. Jain and P. Burke, "Nanotube Electronics for RF Applications", *Nature Nanotechnology*, in press, (2009).

$$v_{drift} = \begin{cases} \mu E & E = V_{ds}/L_{gate} \text{ small} \Leftrightarrow L_{gate} \text{ large} \\ v_{sat} & E = V_{ds}/L_{gate} \text{ large} \Leftrightarrow L_{gate} \text{ small} \end{cases}$$

$$f_T = \begin{cases} \mu(V_{gate} - V_T)/\pi L_{gate}^2 & L_{gate} \text{ "large"} \\ v_{sat}/2\pi L_{gate} & L_{gate} \text{ "small"} \end{cases}$$

$$f_{max} \approx \frac{f_T}{2[g_d(R_{parasitic,s} + R_{gate}) + 2\pi f_T C_{parasitic,gd} R_{gate}]^{1/2}}$$





# Dense arrays on quartz

- What is length, diameter, chirality, impurity density of each tube on wafer scale?
- Raman?
- PL?
- Other techniques?

L. Ding, D. Yuan and J. Liu, "Growth of High-Density Parallel Arrays of Long Single-Walled Carbon Nanotubes on Quartz Substrates", *J. Am. Chem. Soc.*, **130**, 5428-5429, (2008).

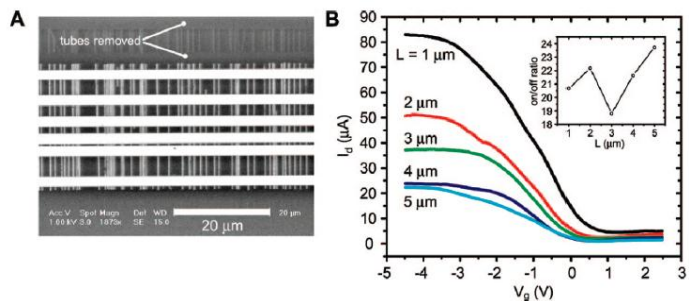
C. Kocabas, S. H. Hur, A. Gaur, M. A. Meitl, M. Shim and J. A. Rogers, "Guided Growth of Large-Scale, Horizontally Aligned Arrays of Single-Walled Carbon Nanotubes and Their Use in Thin-Film Transistors", *Small*, **1**, 1110-1116, (2005).

S. Han, X. Liu and C. Zhou, "Template-Free Directional Growth of Single-Walled Carbon Nanotubes on a- and R-Plane Sapphire", *J. Am. Chem. Soc.*, **127**, 5294-5295, (2005).

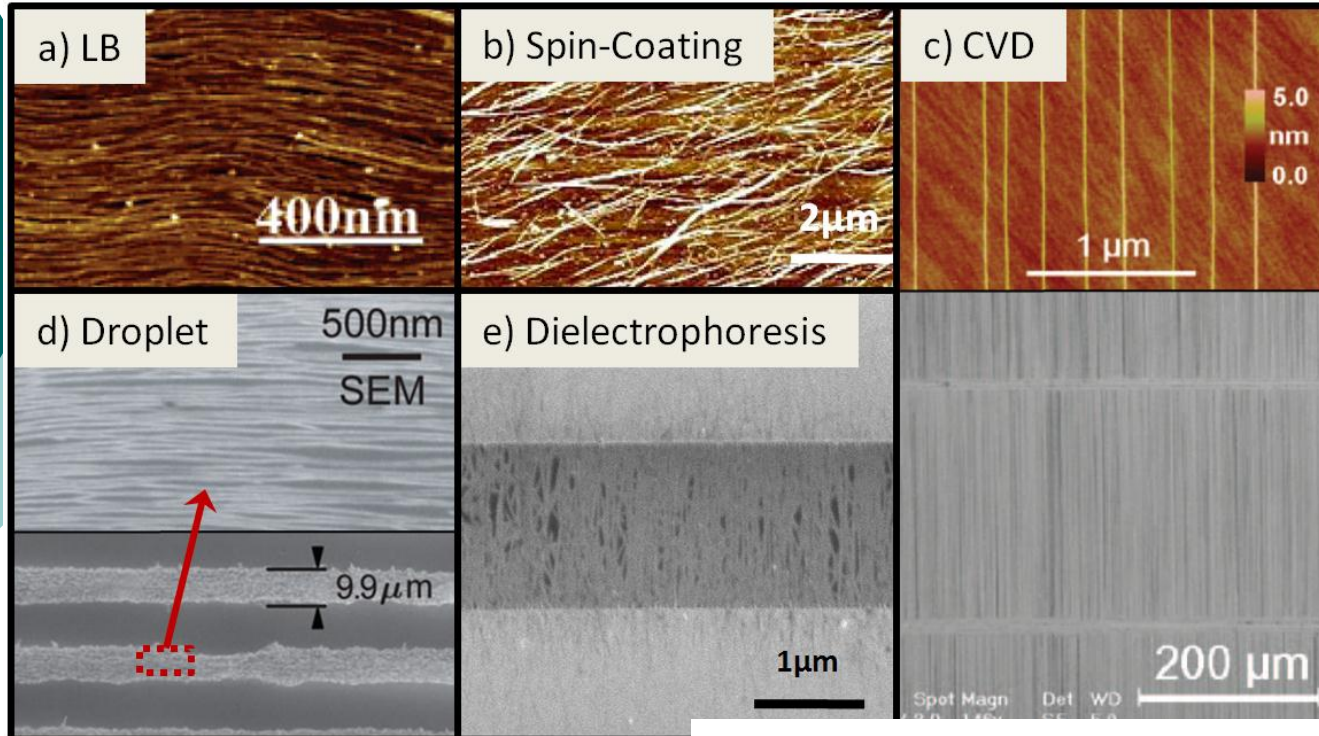
Z. Chongwu, L. Xiaolei, H. Song and I. Fumiaki, "A Nanotube-on-Insulator (Noi) Approach toward Scalable and Integratable Nanotube Devices on Sapphire", in *Solid-State and Integrated Circuit Technology, 2006. ICSICT '06. 8th International Conference on. 2006. p. 1065-1067.*

W. Zhou, C. Rutherglen and P. Burke, "Wafer Scale Synthesis of Dense Aligned Arrays of Swnts", *Nano Research*, **1**, 158-165, (2008).

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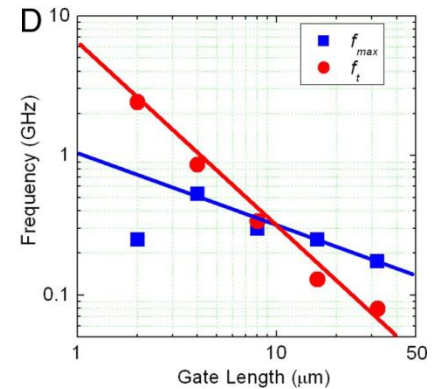
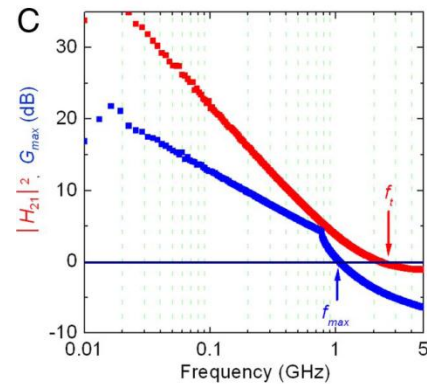
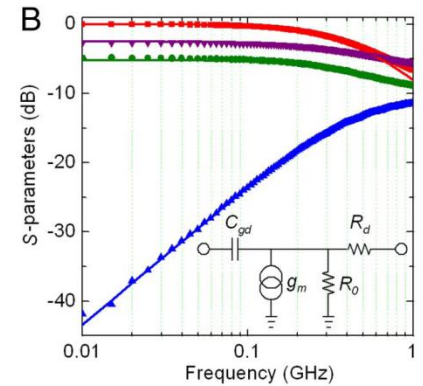
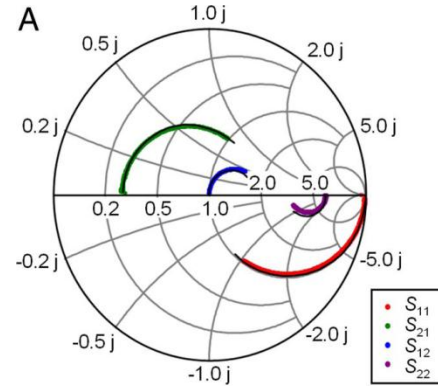
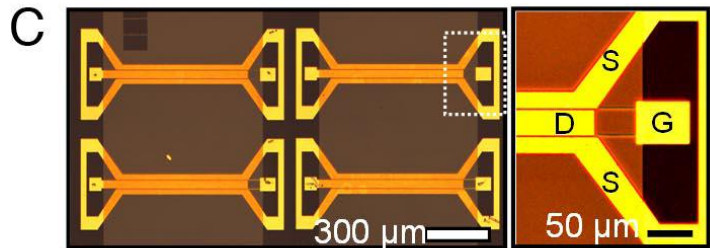
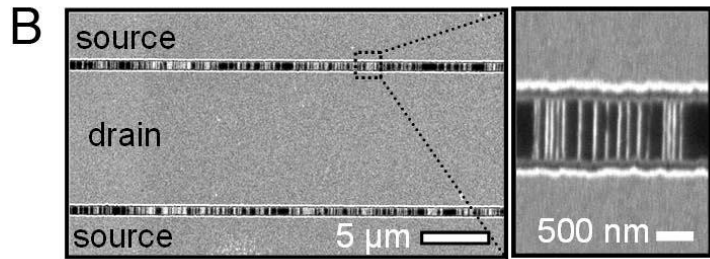
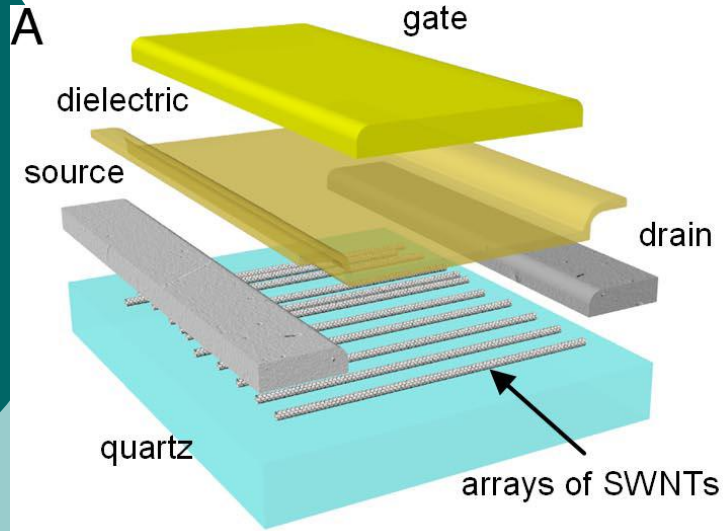
# Alignment: Status & Goals



C. Rutherglen, D. Jain and P. Burke,  
 "Nanotube Electronics for RF Applications",  
*Nature Nanotechnology*, in press, (2009).

Property/Parameter	Target Value or Range	Justification
Diameter	1.5 – 2.0 nm	•Current is largest in this range <sup>107,108</sup> .
Chirality	semiconducting & same (n,m)	•To obtain identical transport properties.
Purity	>99%	• No metallics for high gain and $f_{Max}$
Length	> 1 µm	•SWNT length must be longer than the intended electrode gap channel length.
Density	>10 SWNT/µm	• Reduces parasitic capacitance, increases current carrying capacity, and improves impedance matching.
Alignment	All parallel	•Result in higher transconductance, and denser SWNT packing
Uniformity	Wafer scale	•Essential for large scale processing.

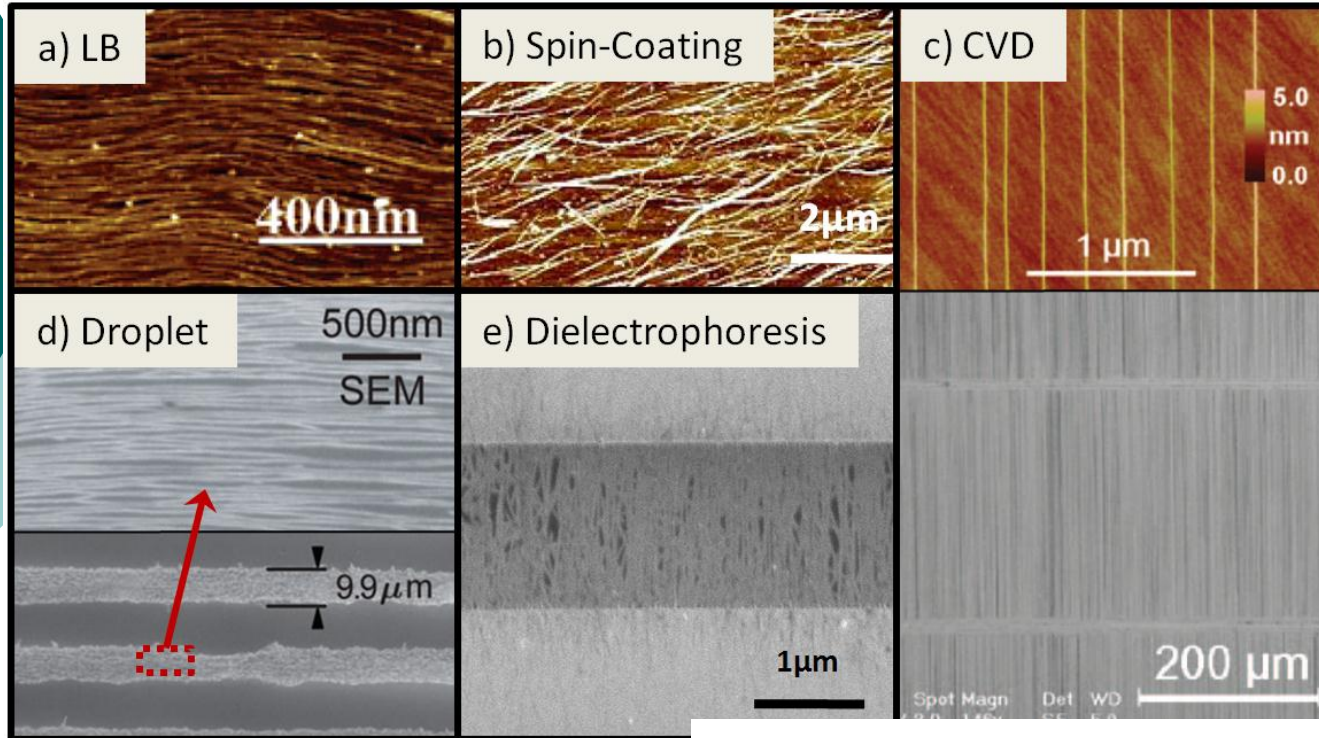
# quartz



E. Cubukcu, F. Degirmenci, C. Kocabas, M. A. Zimmler, J. A. Rogers and F. Capasso, "Aligned Carbon Nanotubes as Polarization-Sensitive, Molecular near-Field Detectors", *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 2495-2499, (2009).



# Alignment: Status & Goals

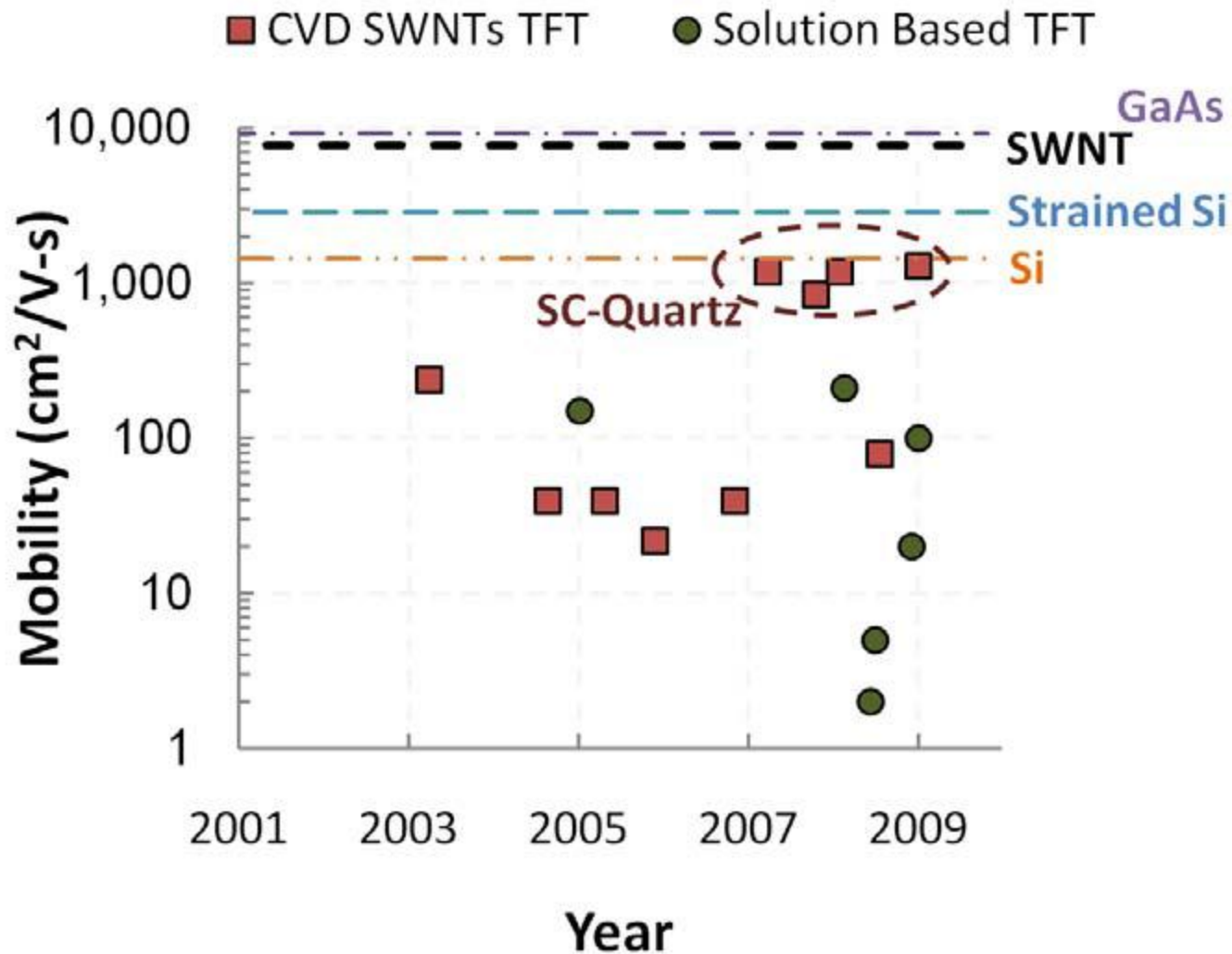


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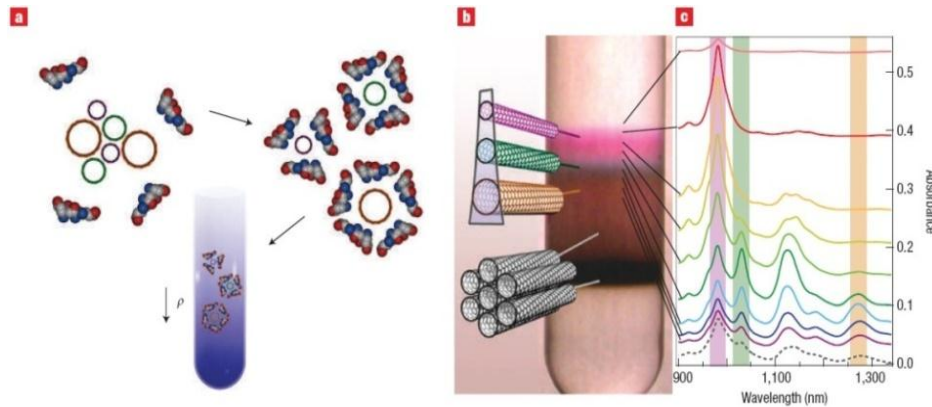
# Mobilities



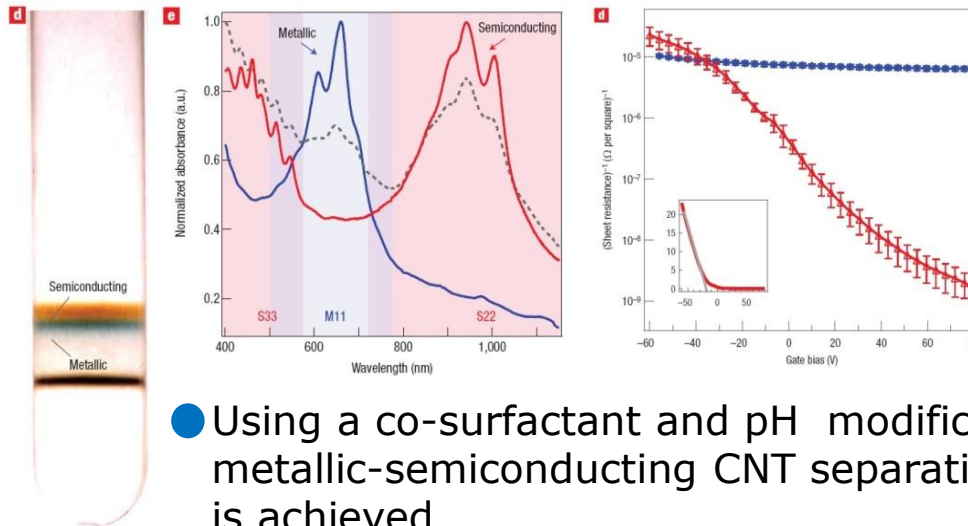
C. Rutherglen, D. Jain and P. Burke, "Nanotube Electronics for Radiofrequency Applications", *Nature Nanotechnology*, **4**, 811-819, (2009).



# (n,m) enrichment



- CNTs are surfactant encapsulated and separate by density during centrifugation

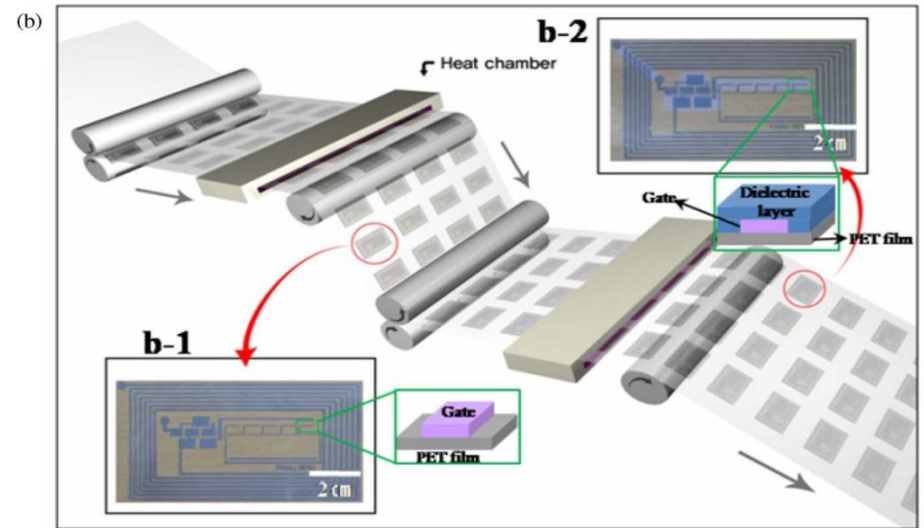
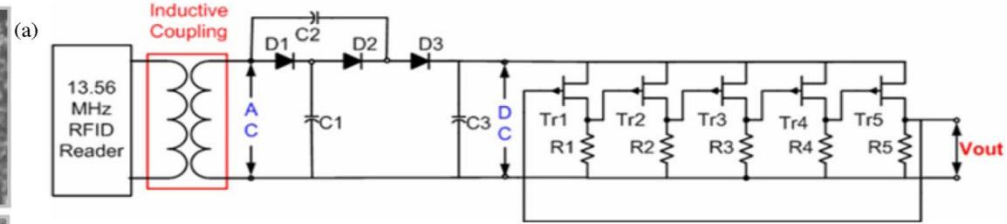
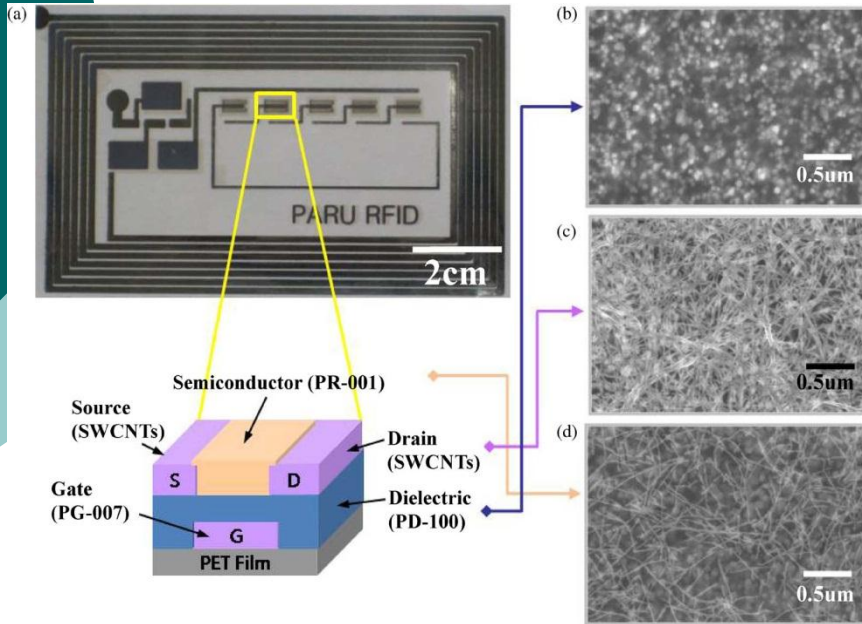


- Using a co-surfactant and pH modification, metallic-semiconducting CNT separation is achieved

M. Hersam, "Progress Towards Monodisperse Single-Walled Carbon Nanotubes", *Nature Nanotechnology*, **3**, 387-394, (2008).



# Applications: Low Cost- RFID

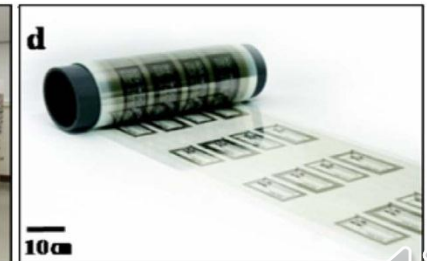


Mob ~ 5 & on/off ratio 100

Minhun, J., K. Jaeyoung, et al. (2010). "All-Printed and Roll-to-Roll-Printable 13.56-MHz-Operated 1-bit RF Tag on Plastic Foils." *Electron Devices, IEEE Transactions on* **57(3): 571-580.**

Our Goal:

**Mob ~ 100 &  
on/off ratio 100000**



# Dense arrays on quartz

- What is length, diameter, chirality, impurity density of each tube on wafer scale?
- Raman?
- PL?
- Other techniques?

L. Ding, D. Yuan and J. Liu, "Growth of High-Density Parallel Arrays of Long Single-Walled Carbon Nanotubes on Quartz Substrates", *J. Am. Chem. Soc.*, **130**, 5428-5429, (2008).

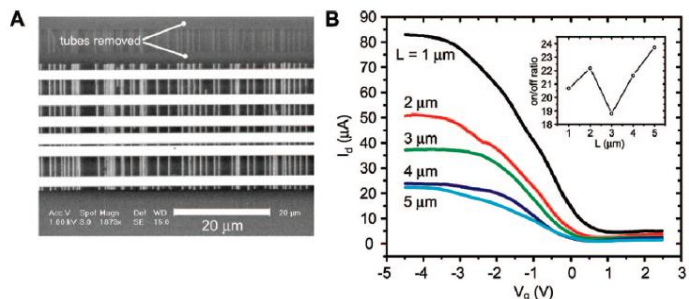
C. Kocabas, S. H. Hur, A. Gaur, M. A. Meitl, M. Shim and J. A. Rogers, "Guided Growth of Large-Scale, Horizontally Aligned Arrays of Single-Walled Carbon Nanotubes and Their Use in Thin-Film Transistors", *Small*, **1**, 1110-1116, (2005).

S. Han, X. Liu and C. Zhou, "Template-Free Directional Growth of Single-Walled Carbon Nanotubes on a- and R-Plane Sapphire", *J. Am. Chem. Soc.*, **127**, 5294-5295, (2005).

Z. Chongwu, L. Xiaolei, H. Song and I. Fumiaki, "A Nanotube-on-Insulator (Noi) Approach toward Scalable and Integratable Nanotube Devices on Sapphire", in *Solid-State and Integrated Circuit Technology, 2006. ICSICT '06. 8th International Conference on. 2006. p. 1065-1067.*

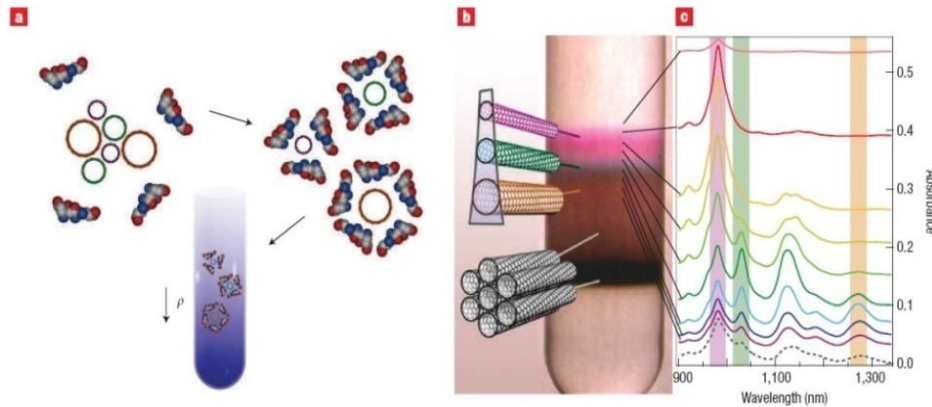
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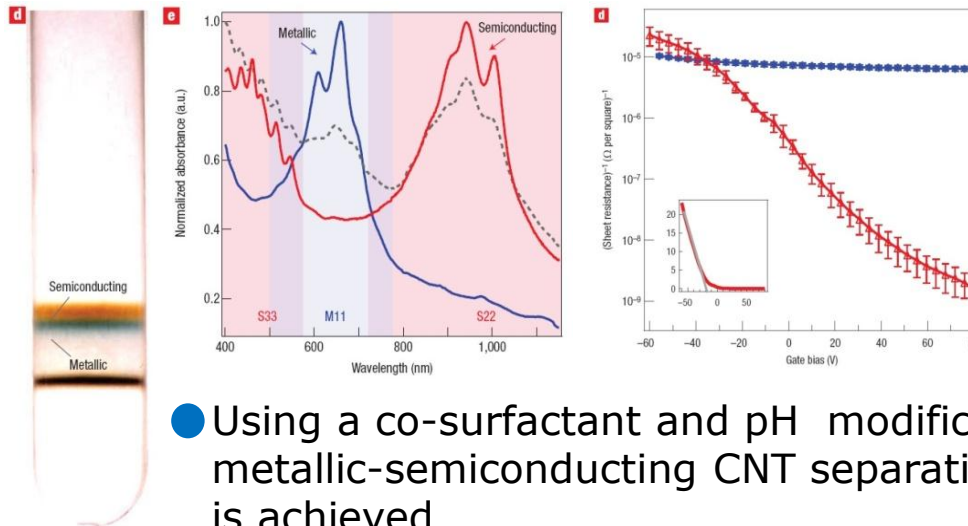




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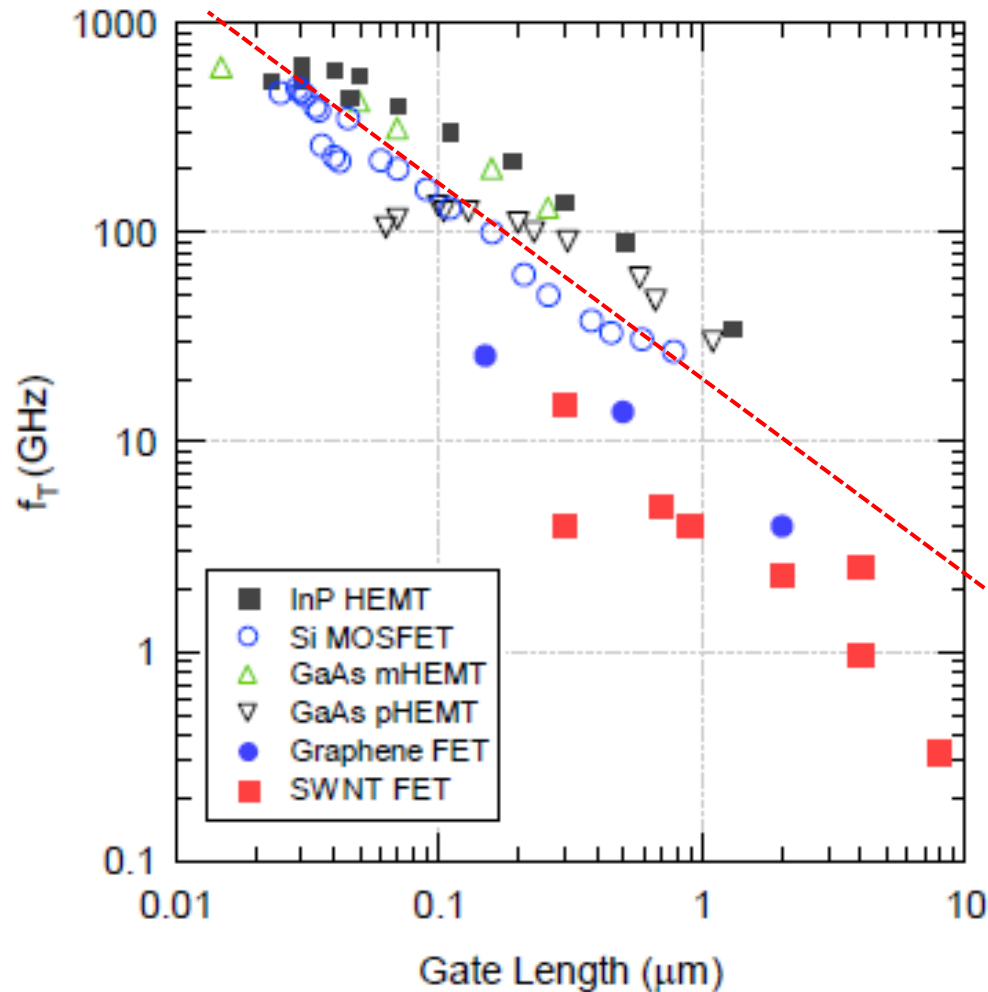
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# Comparison to other semiconductors



Dashed line:  
 $1.2 \times 10^7$  cm/s  $v_{\text{Sat}}$   
(Rogers)

Graphene (Kim)  
0.5 to 5x that value

C. Rutherglen, D. Jain and P. Burke, "Nanotube Electronics for RF Applications", *Nature Nanotechnology*, in press, (**2009**).