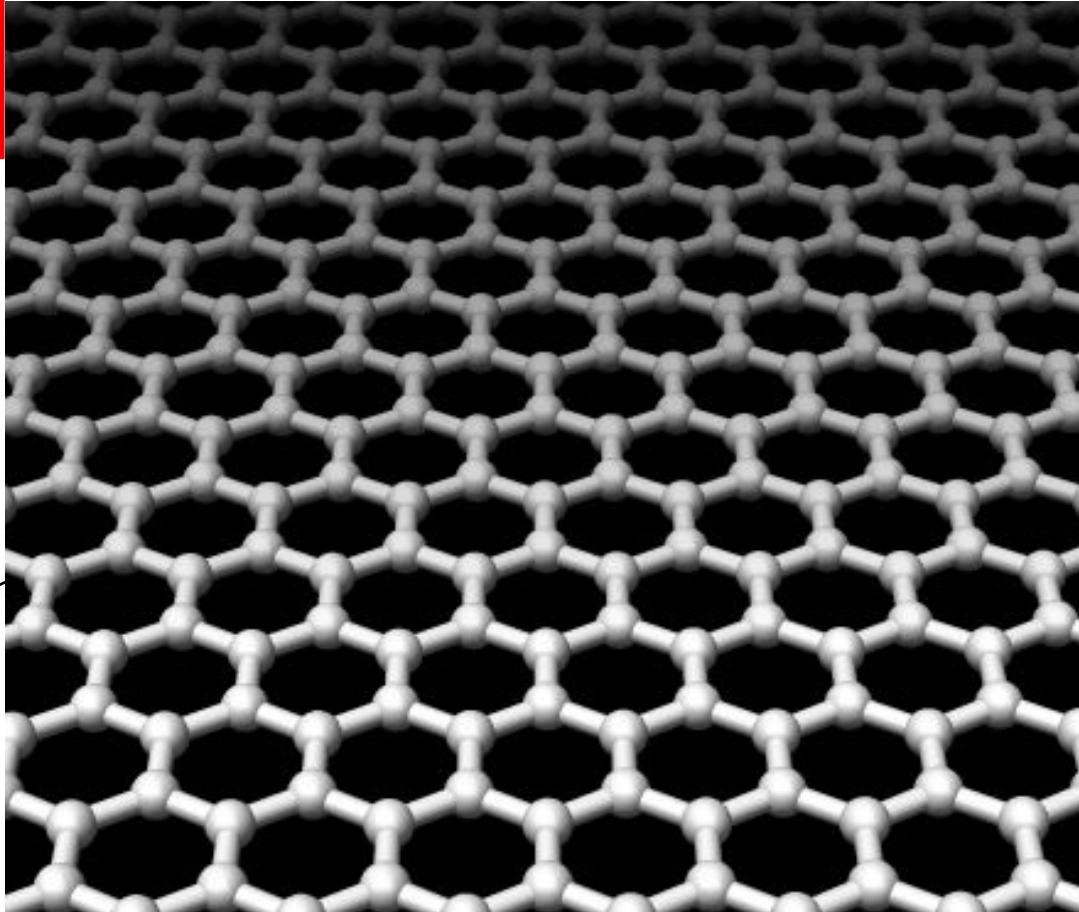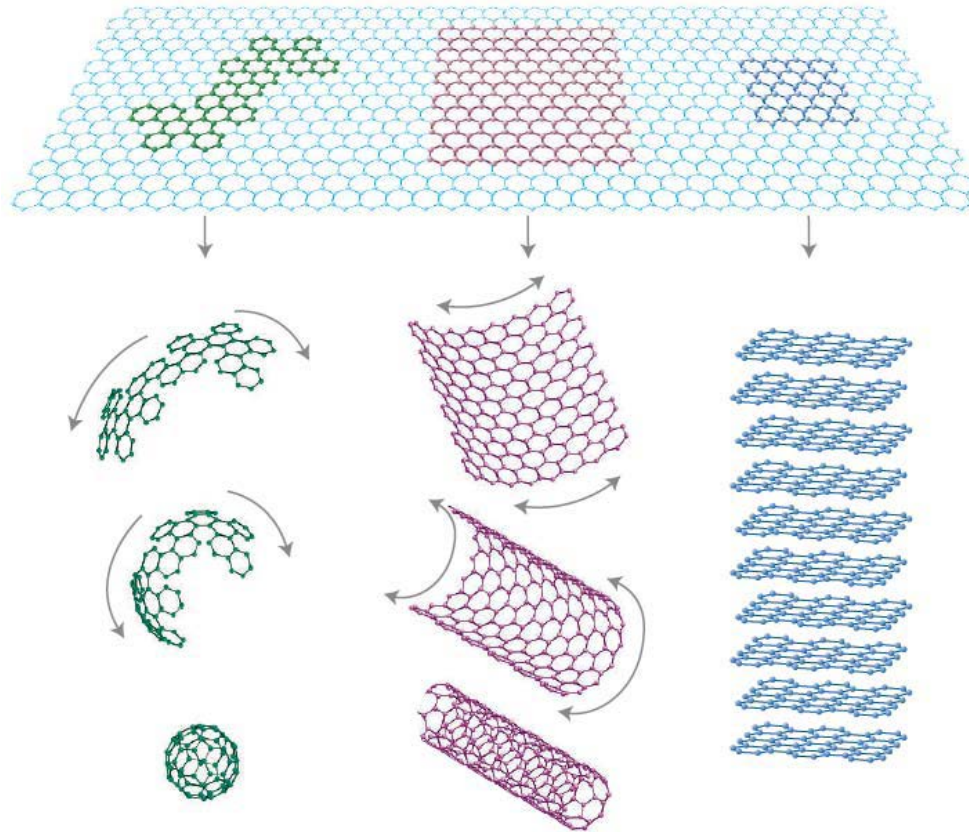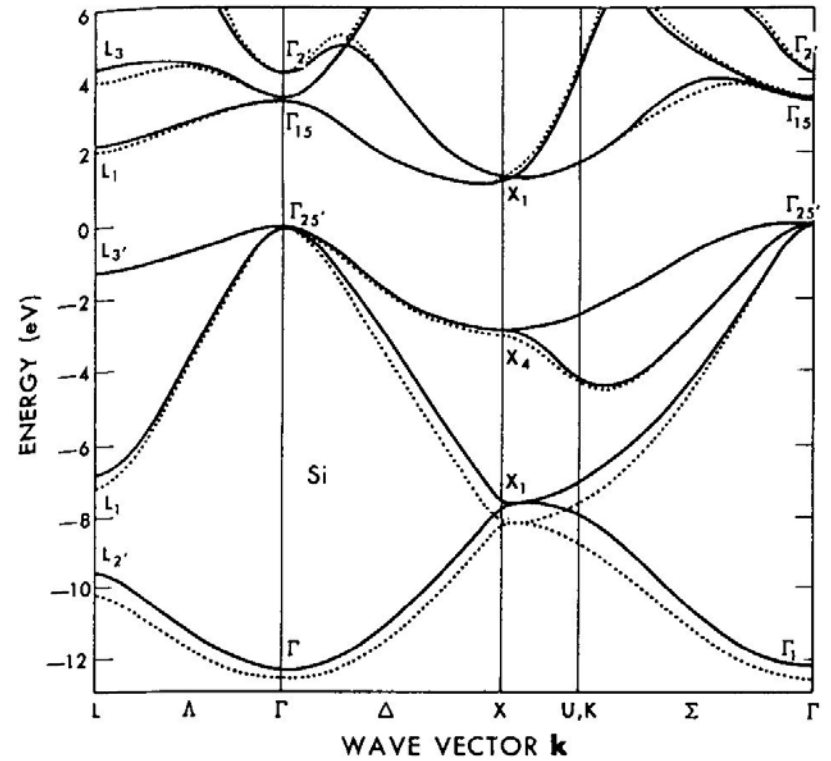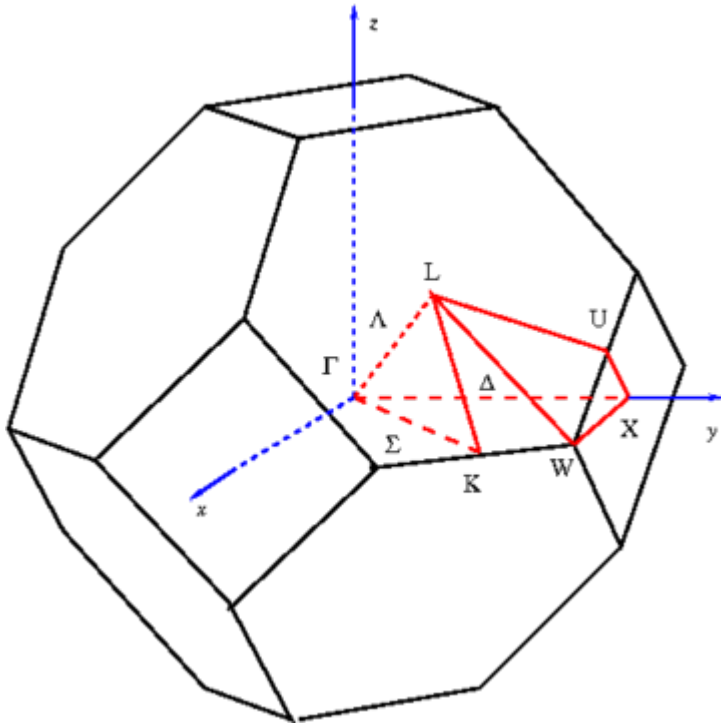# Carbon Electronics

$$R = \, ?$$

Allotropes of Carbon
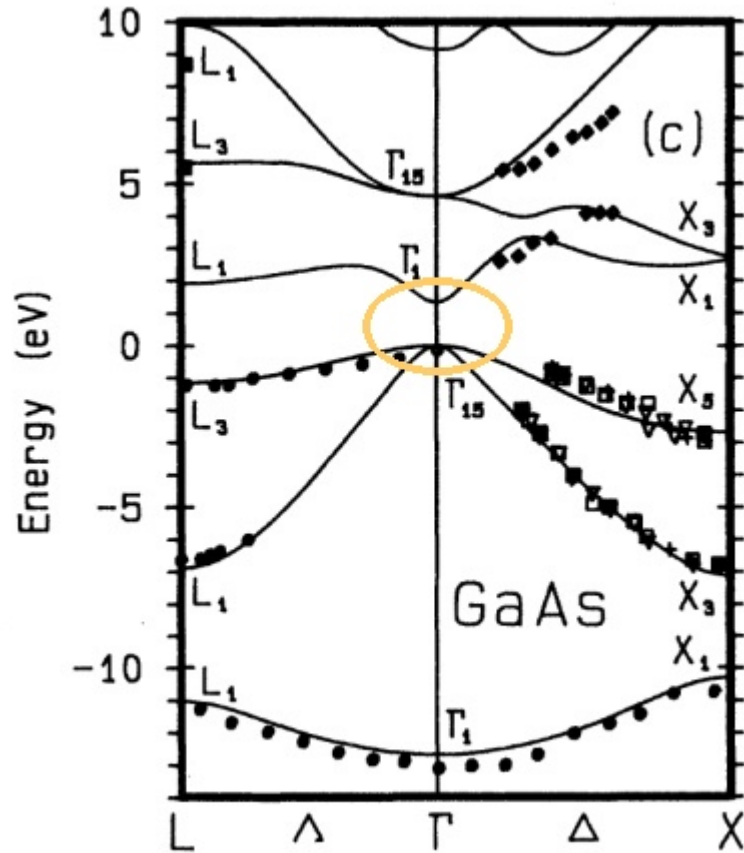

A. Geim and K. Novoselov, "The Rise of Graphene", *Nature Materials*, **6**, 183-191, (**2007**).

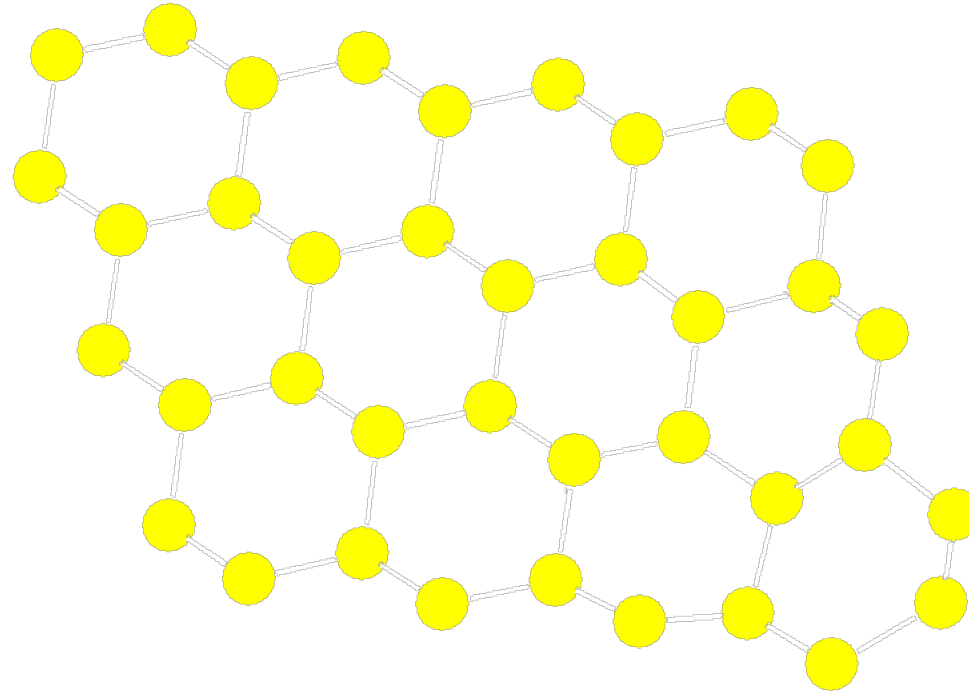# Silicon

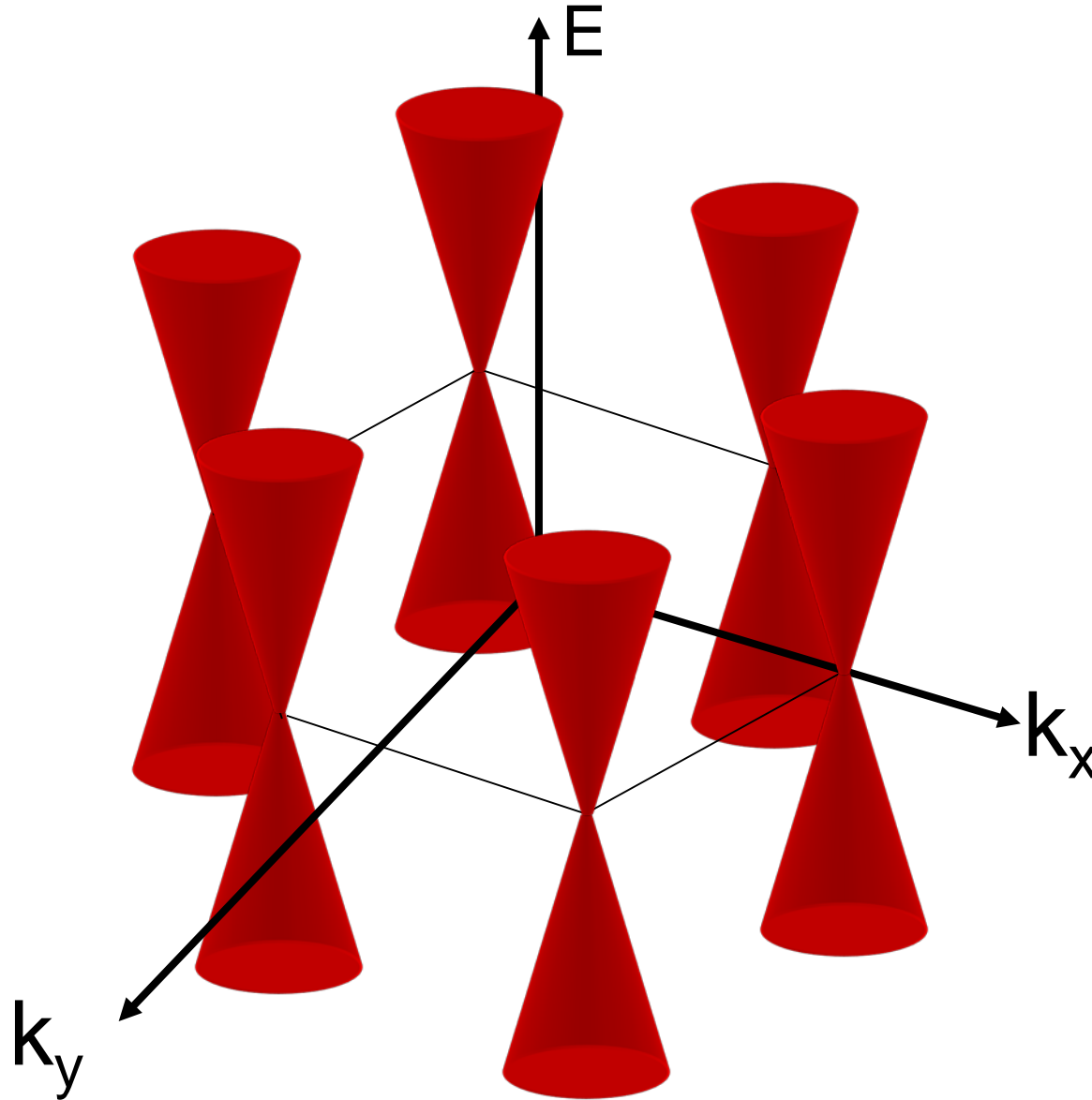EECS 277C Nanotechnology © 2017 P. Burke
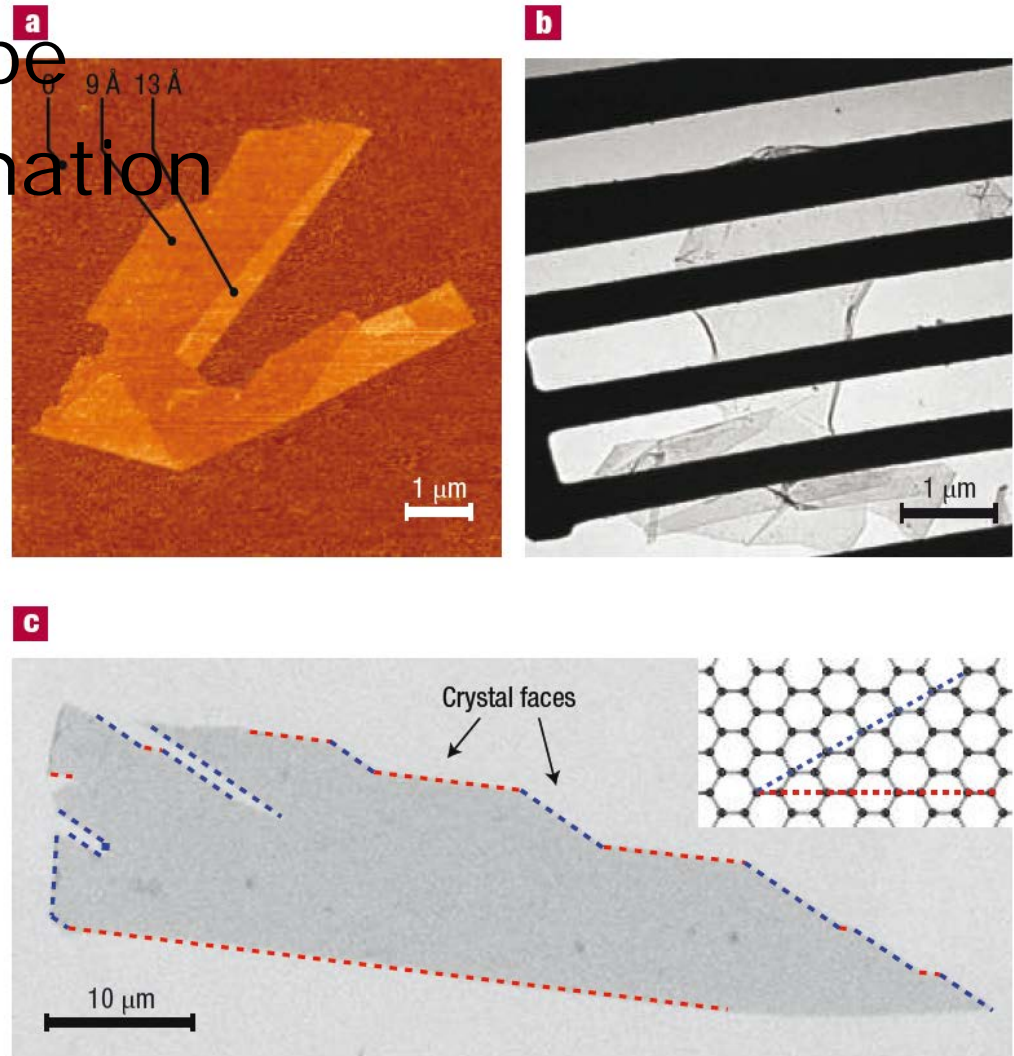
GaAs

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**).
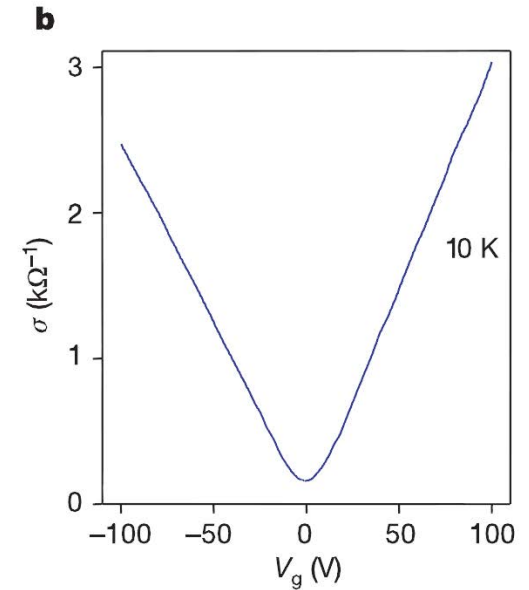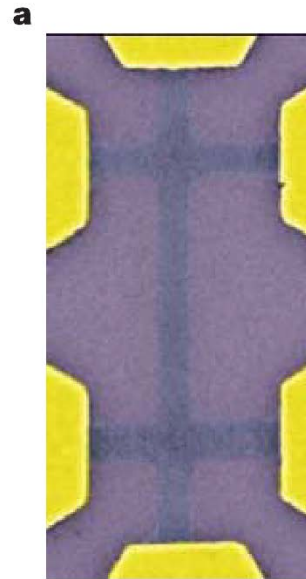
Transport (back gate)
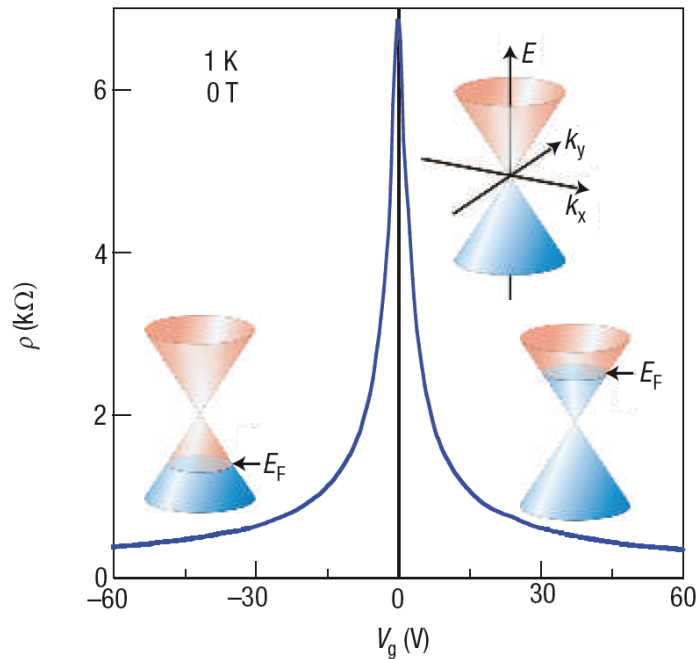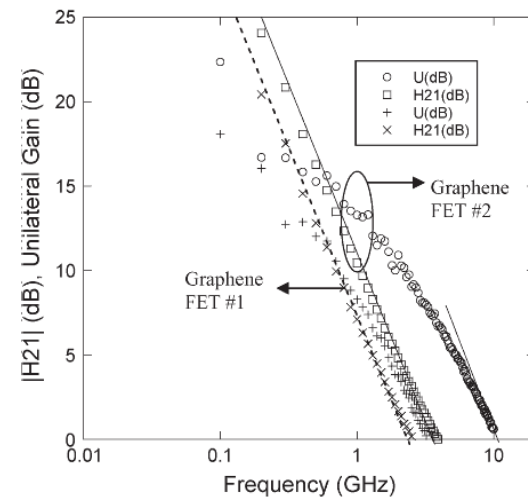

1 K
0 T

ρ (kΩ)

V_g (V)

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

a

b

10 K

σ (kΩ^{-1})

V_g (V)

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

a — Source/drain electrodes, Graphene, Top gate, SiO_2, Si substrate, HfO_2

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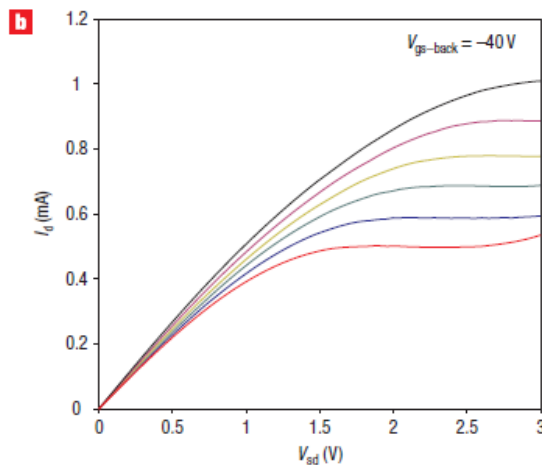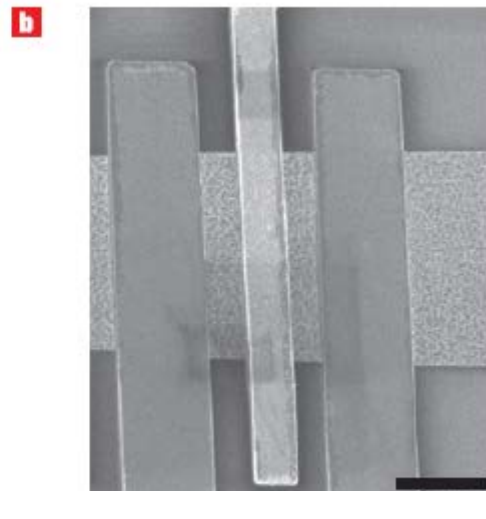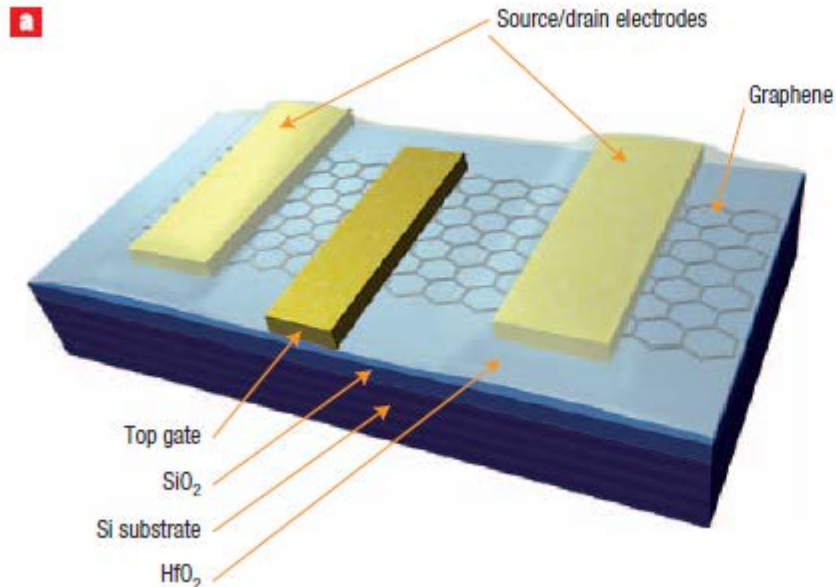
I. Meric, M. Han, A. Young, B. Ozyilmaz, P. Kim and K. Shepard, "Current Saturation in Zero-Bandgap, Top-Gated Graphene Field-Effect Transistors", *Nature Nanotechnology, 3, 654-659, (2008).*

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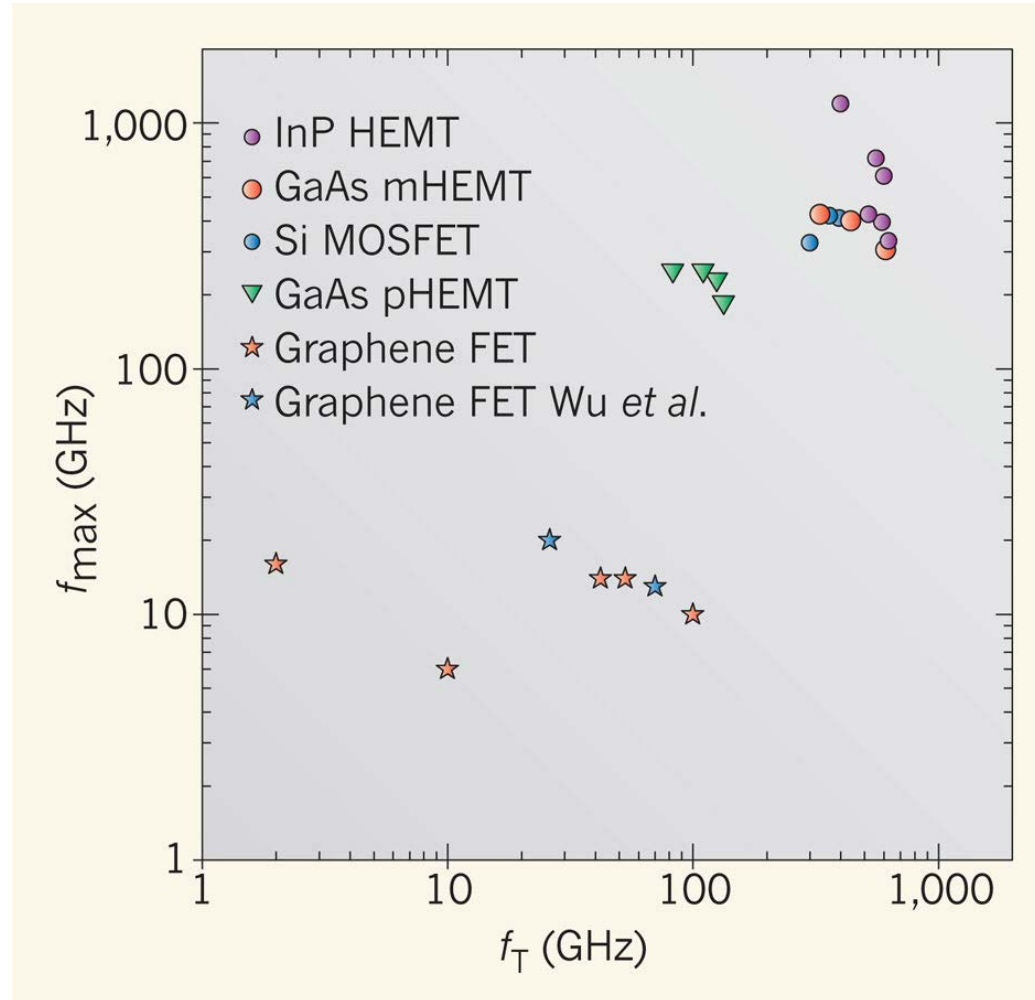
Schwierz, F. (2011). "Electronics: Industry-compatible graphene transistors." Nature **472**(7341): 41-42.

Lectures 14: Carbon Nanotubes

$$R = ?$$
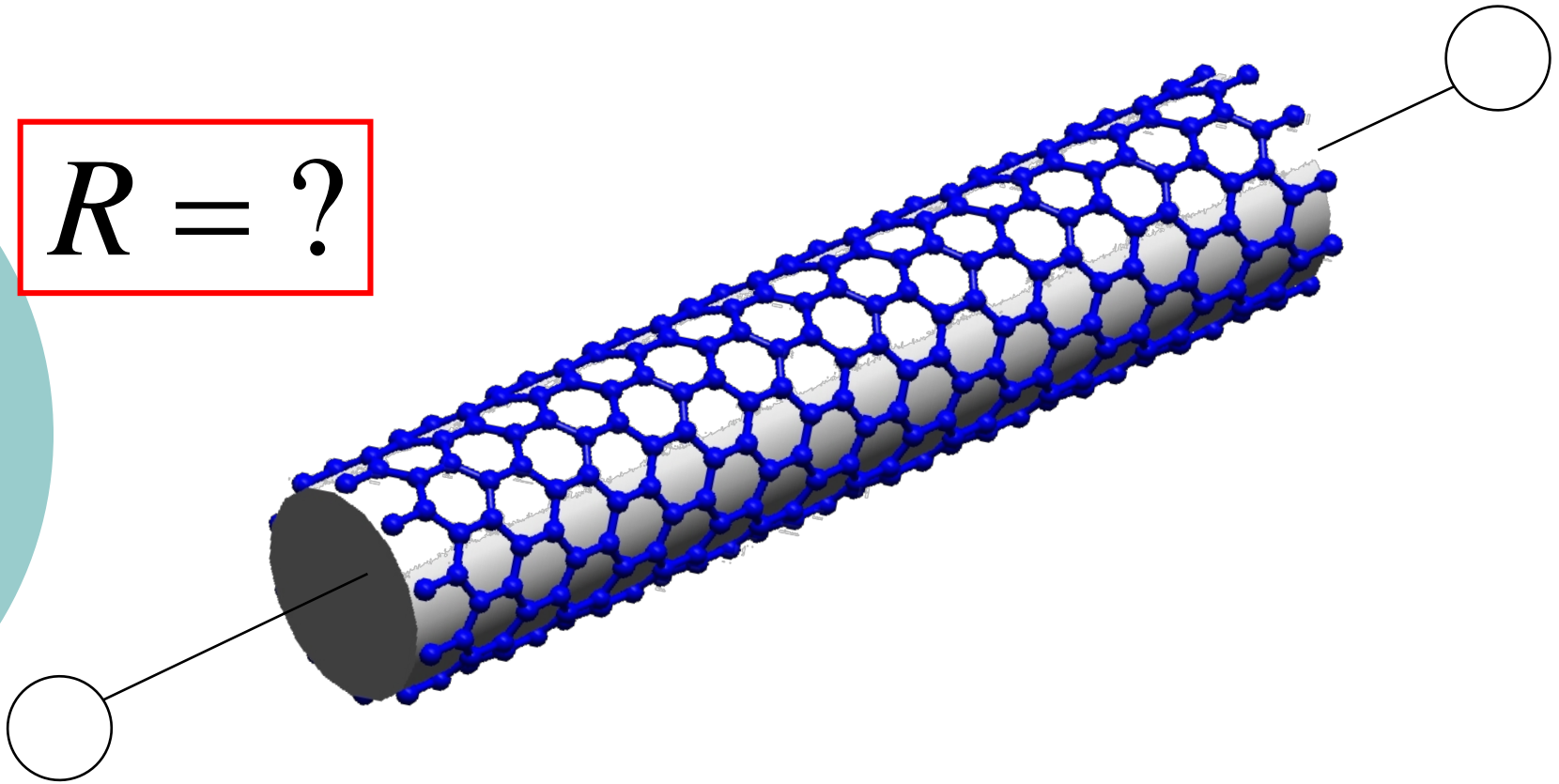
Readings this lecture covers

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

Nanotube: Zig-zag vs. armchair

Armchair

Zig-zag

In between:
Chiral
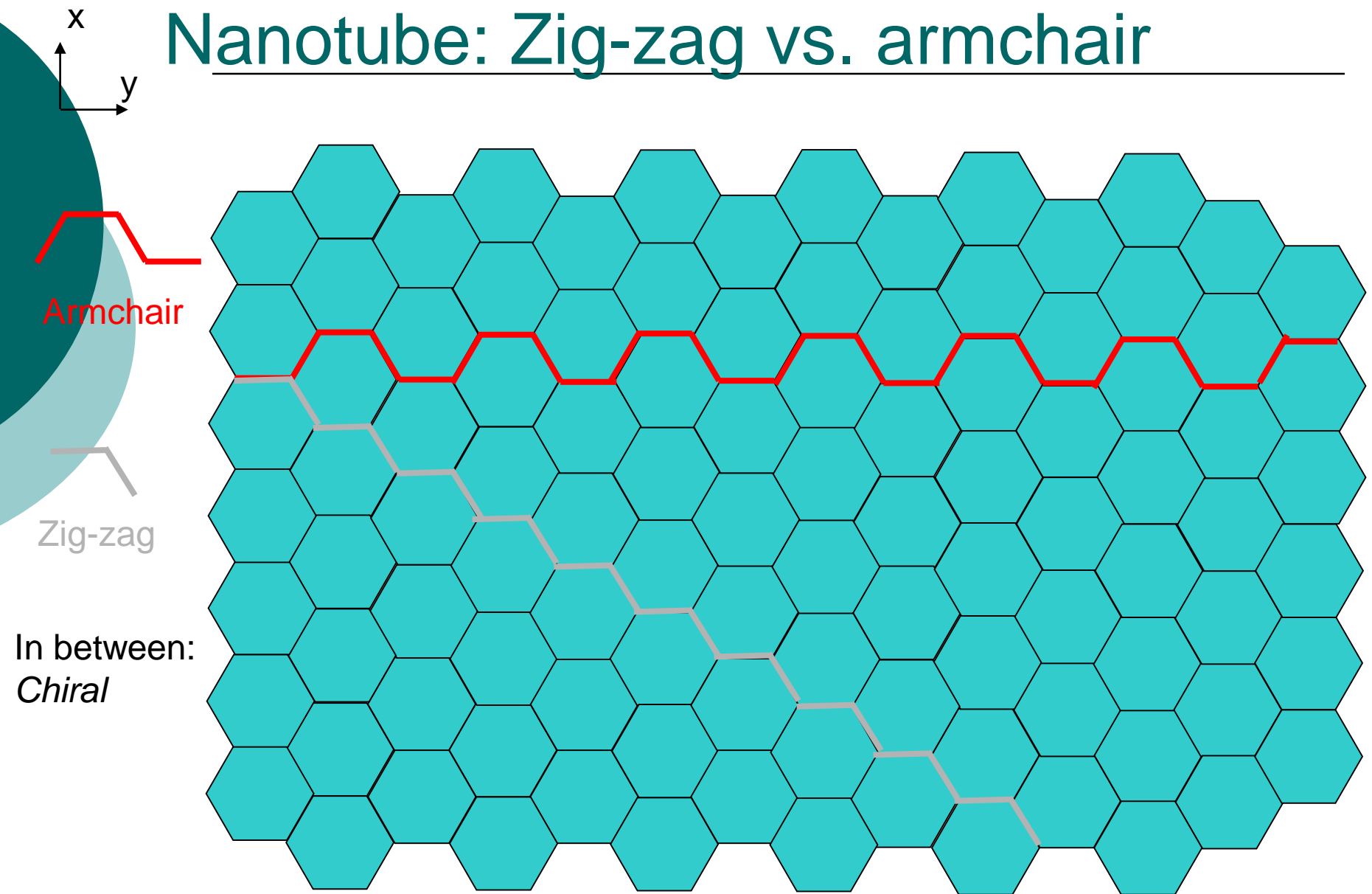
Nanotube: (n,m) description

x

y

a_2 a_1

$6\,a_1 + 2\,a_2$
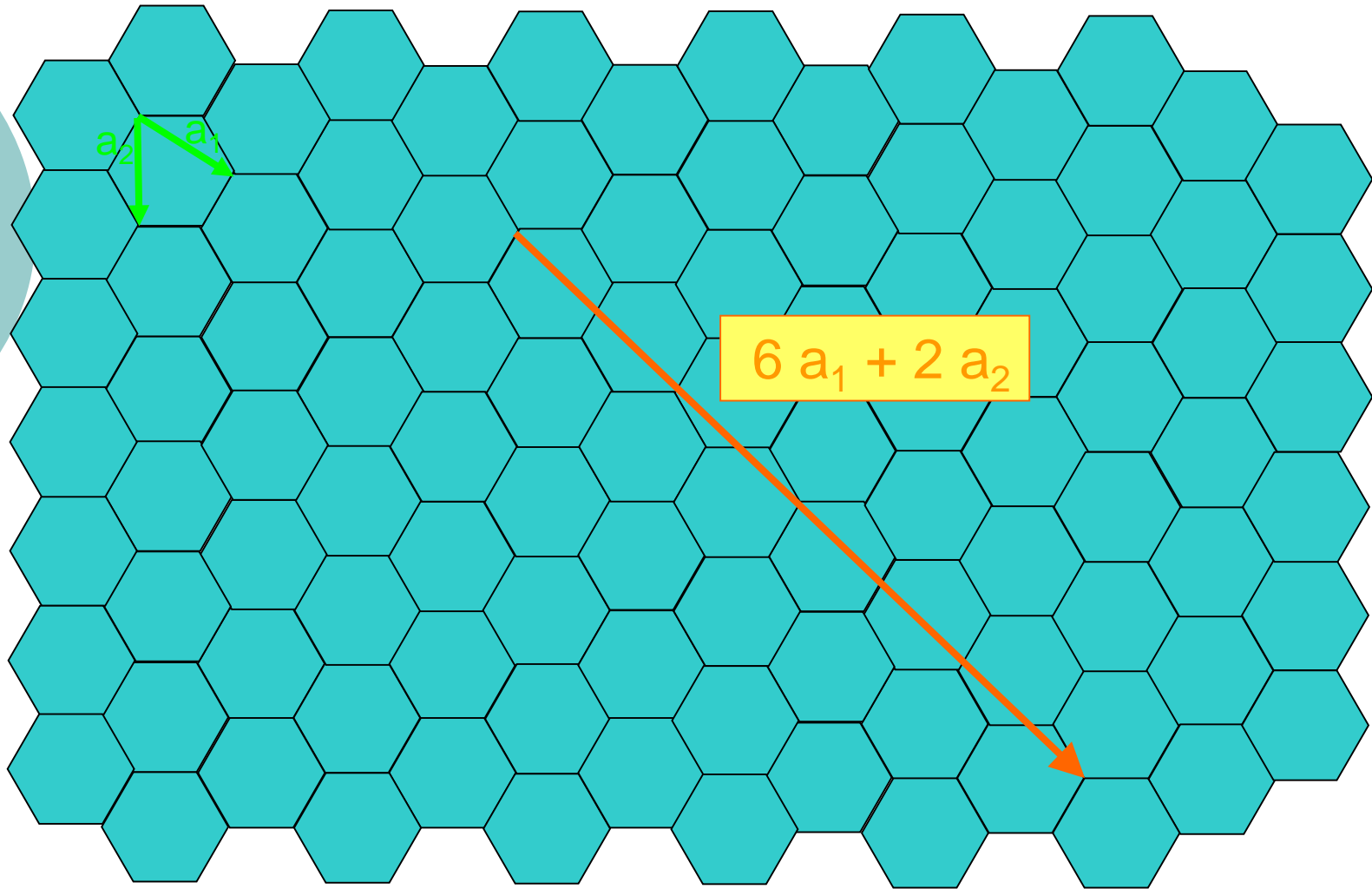
In this example: $(n,m) = (6,2)$

k-vector

- Graphite:
  - Arbitratrary k_x, k_y allowed
- Nanotube:

  $\psi(\phi)=\psi(\phi+2\pi)$

  - k_{perp} spaced by 2/d

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Allowed k-vectors:

k_x

k_y

NT axis

2/d

k-space
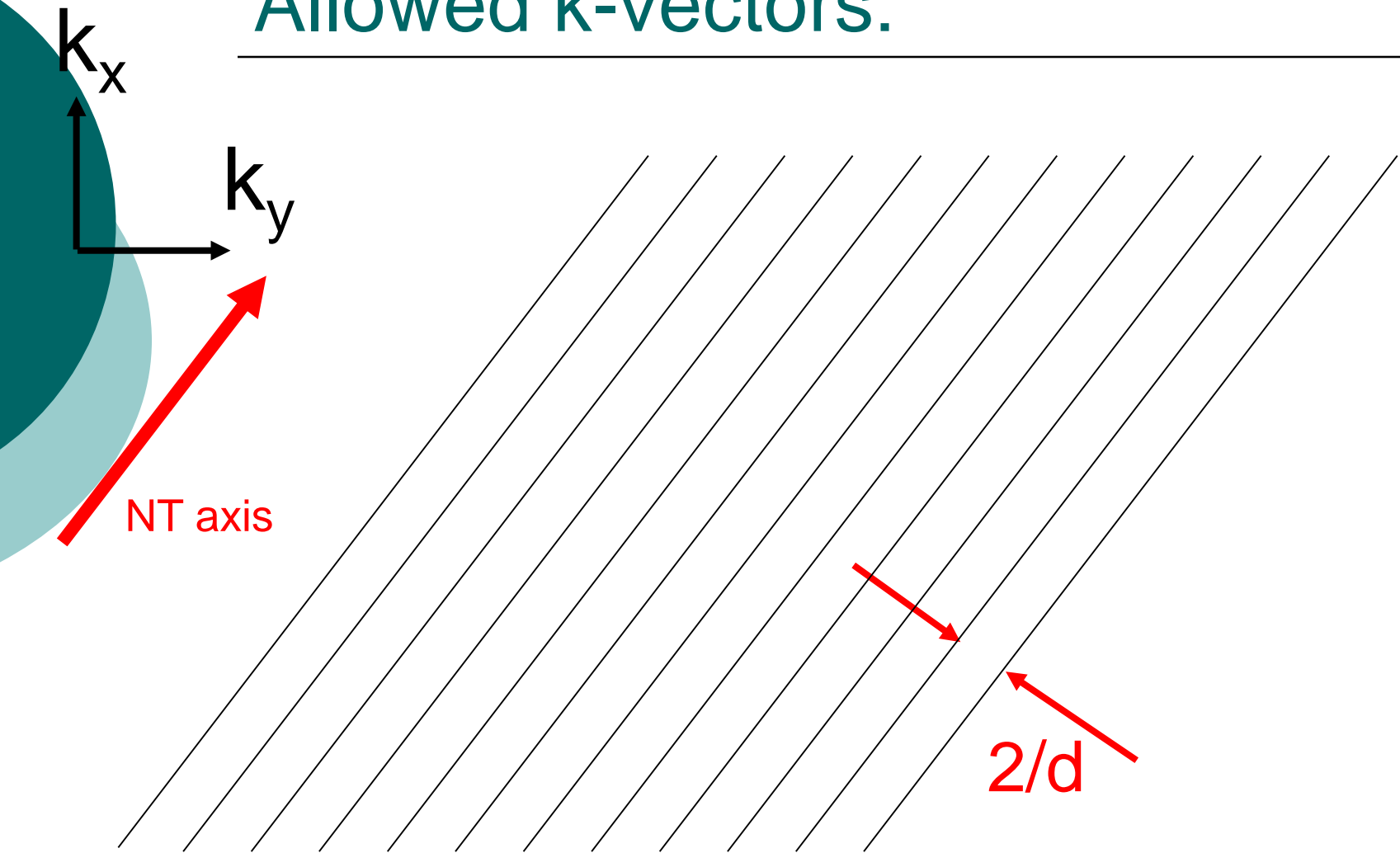
EECS 277C Nanotechnology © 2017 P. Burke
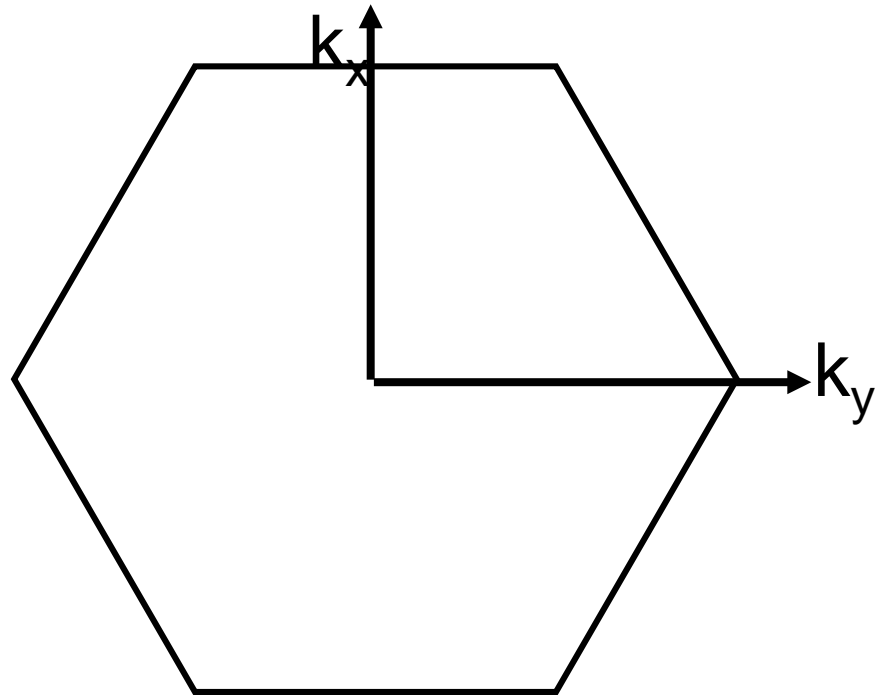
(9,0) armchair nanotube

NT axis

k_x

k_y

2/d
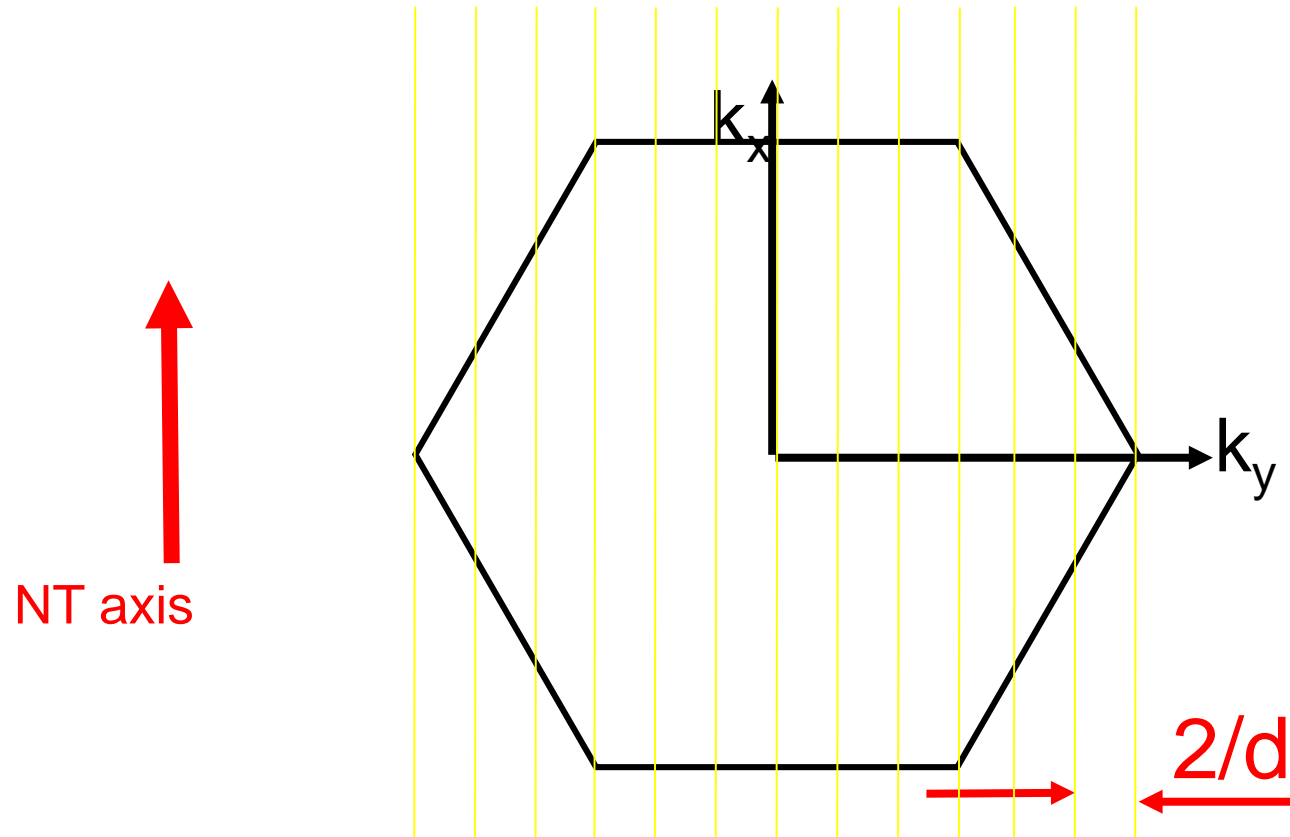
All armchairs are metallic.

$$G = \frac{2e^2}{h} \sum T_n = \frac{4e^2}{h}$$

Semiconducting nanotube

NT axis

k_x

k_y

2/d
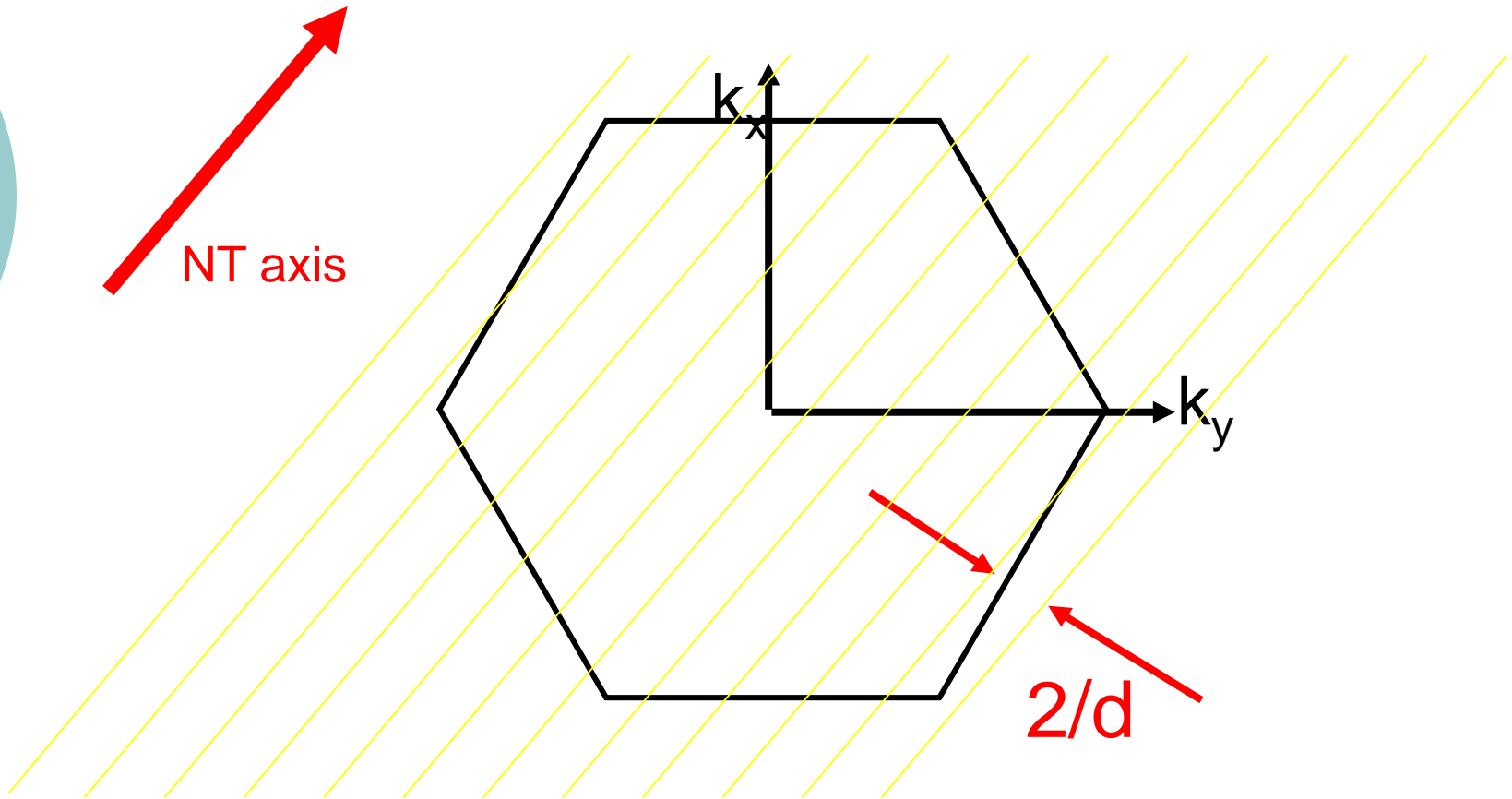
Electrical properties

○ All armchair metallic

○ 33% of zig-zag metallic

○ Semiconducting tubes:

 • Gap = 0.9 eV/d[nm]

Multi-walled nanotube (MWNT)

10 nm
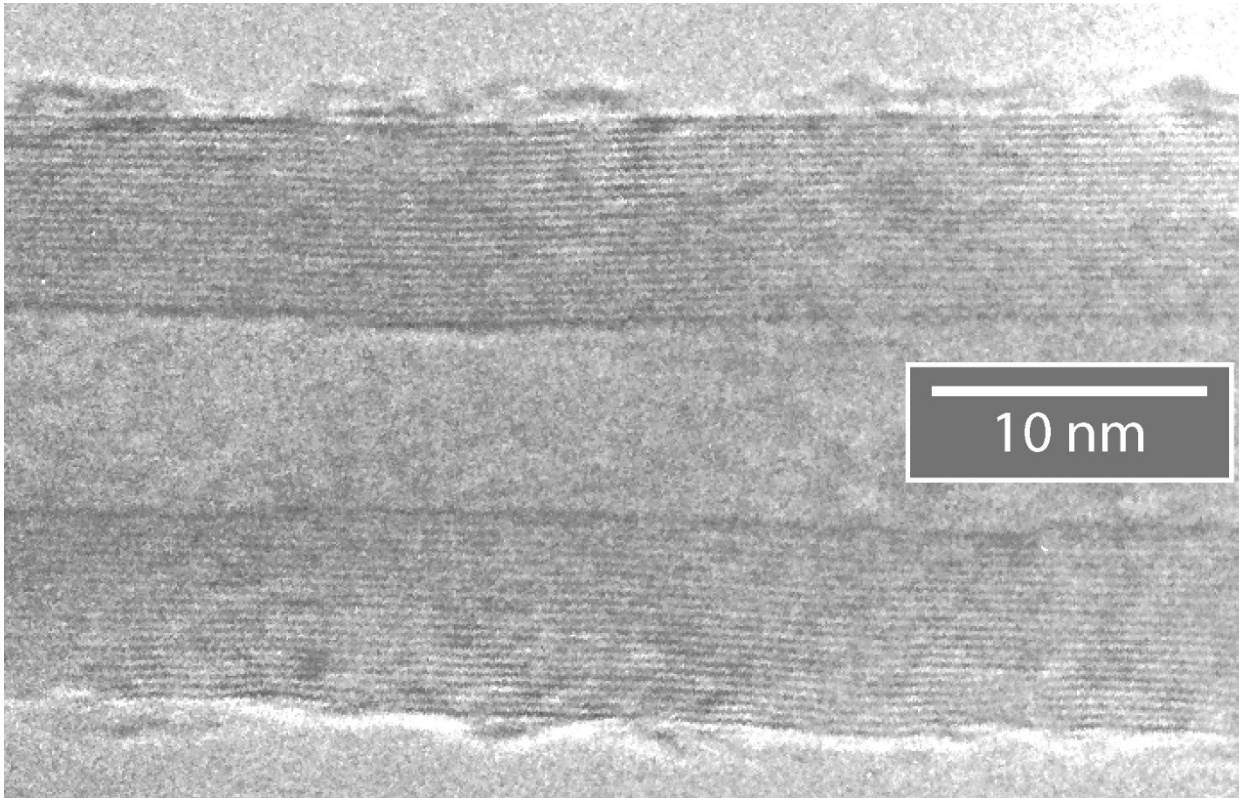
Shengdong Li, unpublished

Growth technologies

○ Arc discharge

○ Laser ablation

○ Chemical vapor deposition (CVD)

CVD

CH$_4$

catalyst on a chip

Oven 1000° C

CH$_4$

Fe doped alumina
nanoparticle (d=10 nm)

Carbon nanotube

Si Wafer

Adapted from Dai in *Carbon Nanotubes*,
by Dresselhaus and Dresselhaus
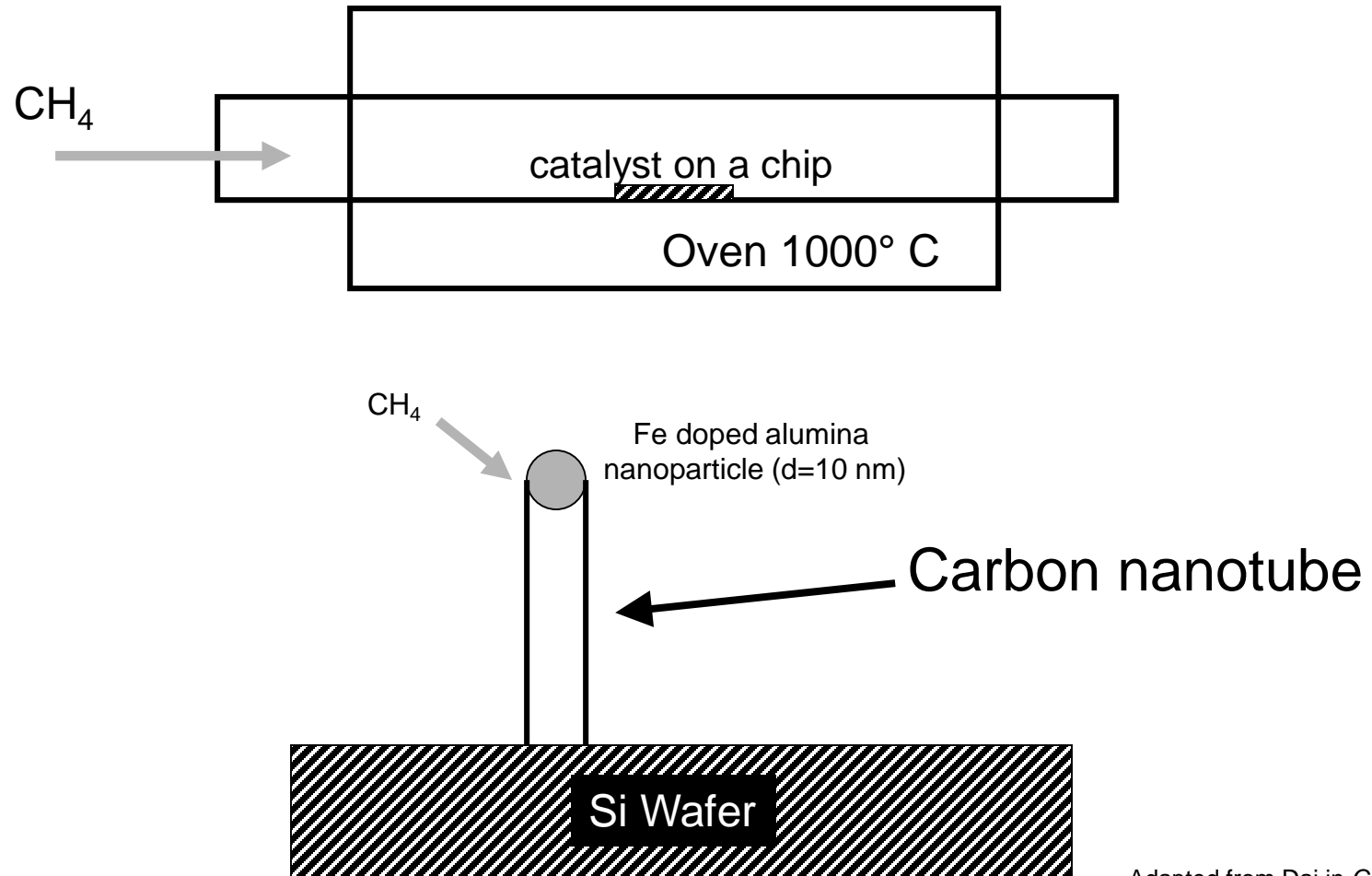
Lithographically defined catalysts

090802c2_6 10.0kV 14.6mm x3.00k 5/8/03 18:46   10.0um
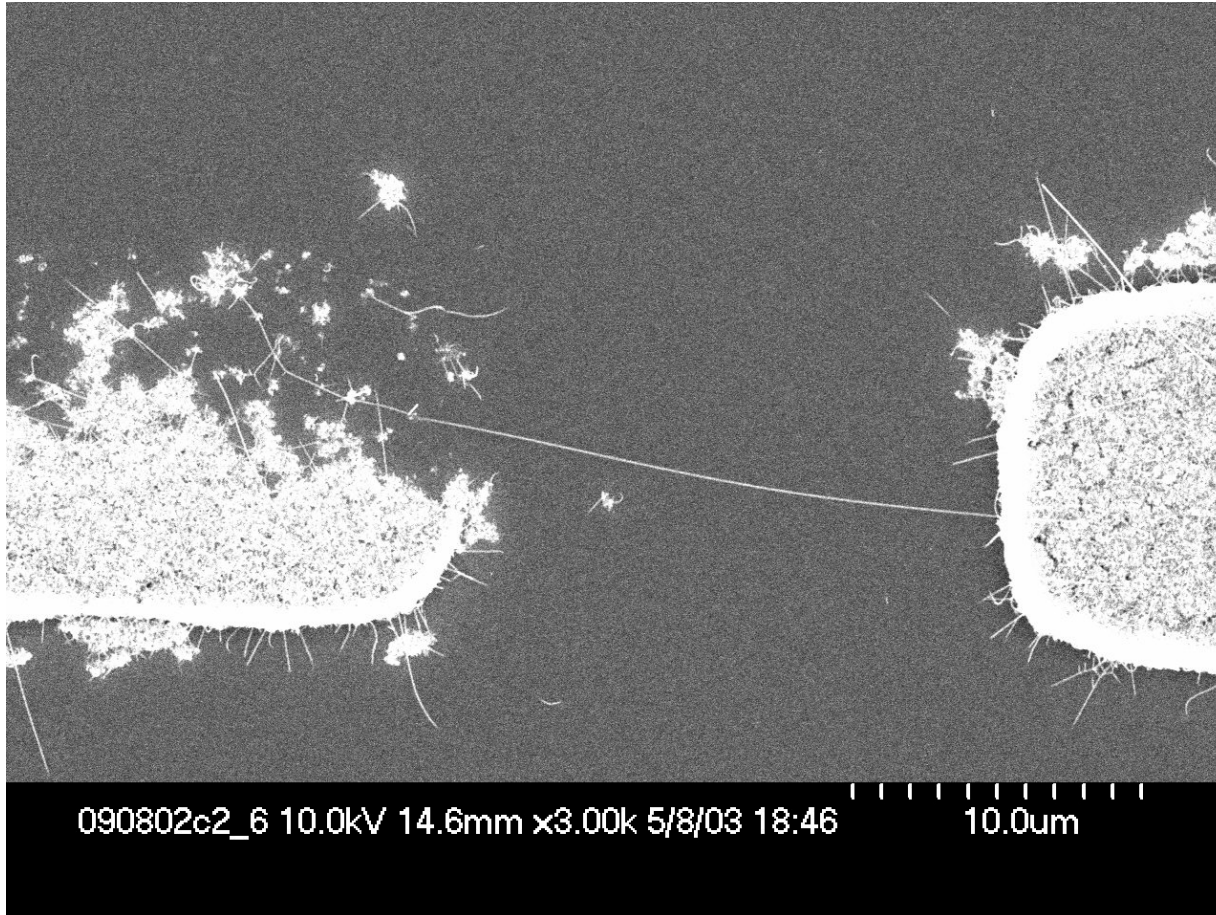
Shengdong Li, unpublished

Single Walled Carbon Nanotube

L = 0.4 cm
d = 1.5 nm

d/L = cm/nm = 10^7

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

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

W

l

$$R = ?$$

L

Ballistic

W l

Ballistic vs. diffusive transport

Diffusive

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

W

l

L

$$R = ?$$

Ballistic

W

l

EECS 277C Nanotechnology © 2017 P. Burke
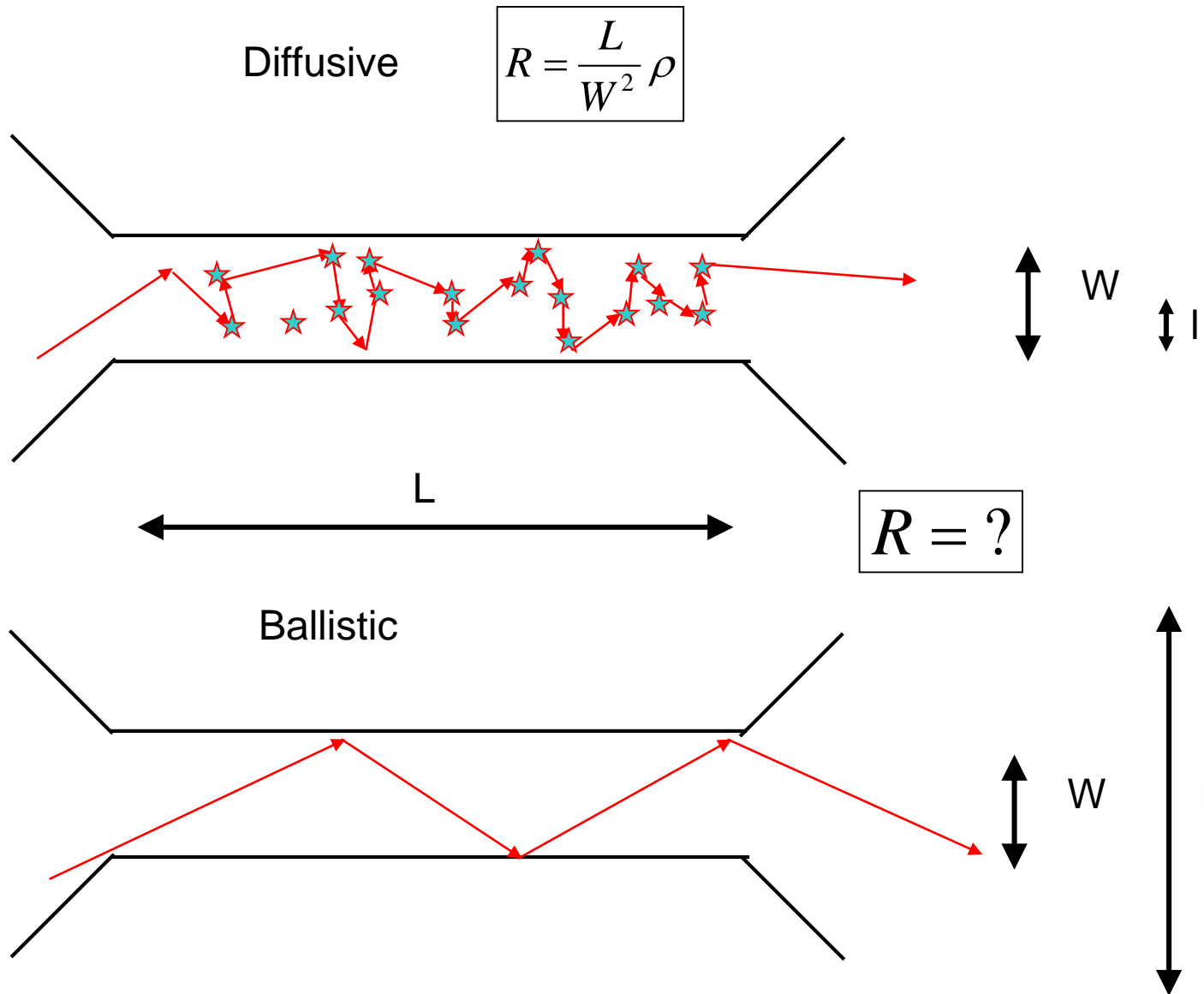
Landauer formula:

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

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

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

EECS 277C Nanotechnology © 2017 P. Burke

Resistance vs. length

R

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

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

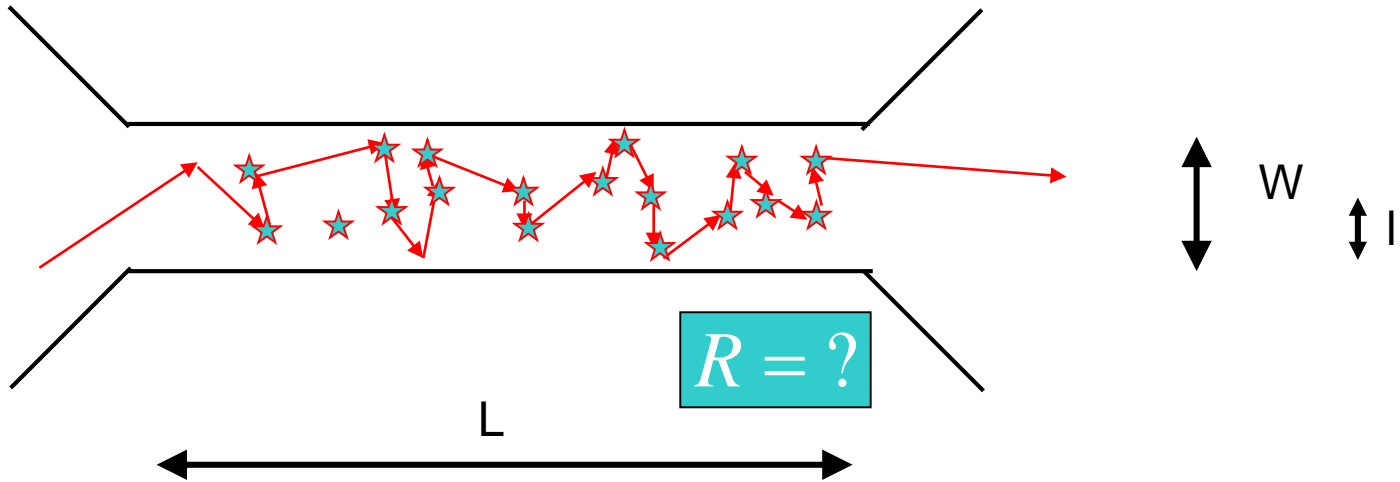Shengdong Li, Zhen Yu, C. Rutherglen, P. J. Burke "Electrical Properties of 0.4 cm Long Single-Walled Carbon Nanotubes", *Nano Letters*, 2004.

Resistance vs. length

$$R = R_{contact} + L \cdot 6\ k\Omega/\mu m$$
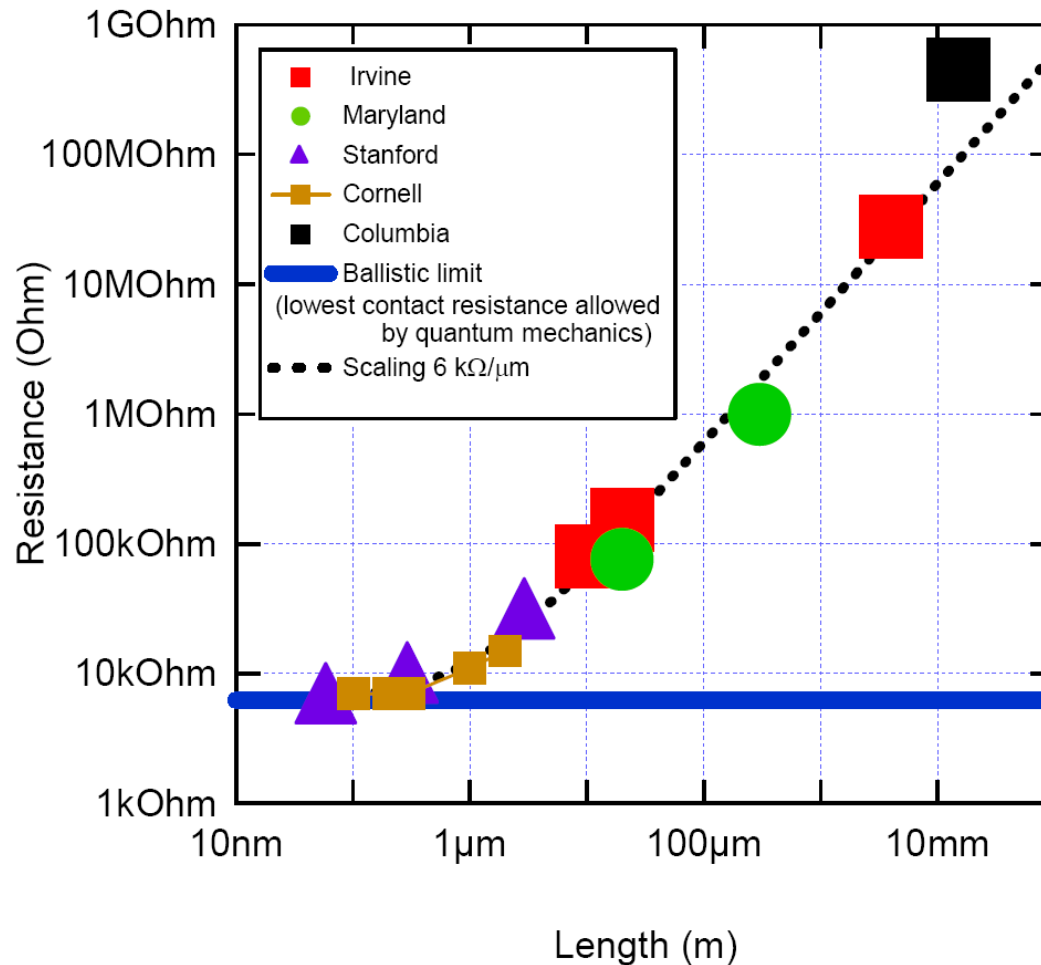
Shengdong Li, Zhen Yu, C. Rutherglen, P. J. Burke "Electrical Properties of 0.4 cm Long Single-Walled Carbon Nanotubes", *Nano Letters*, 2004.

R vs L single tube

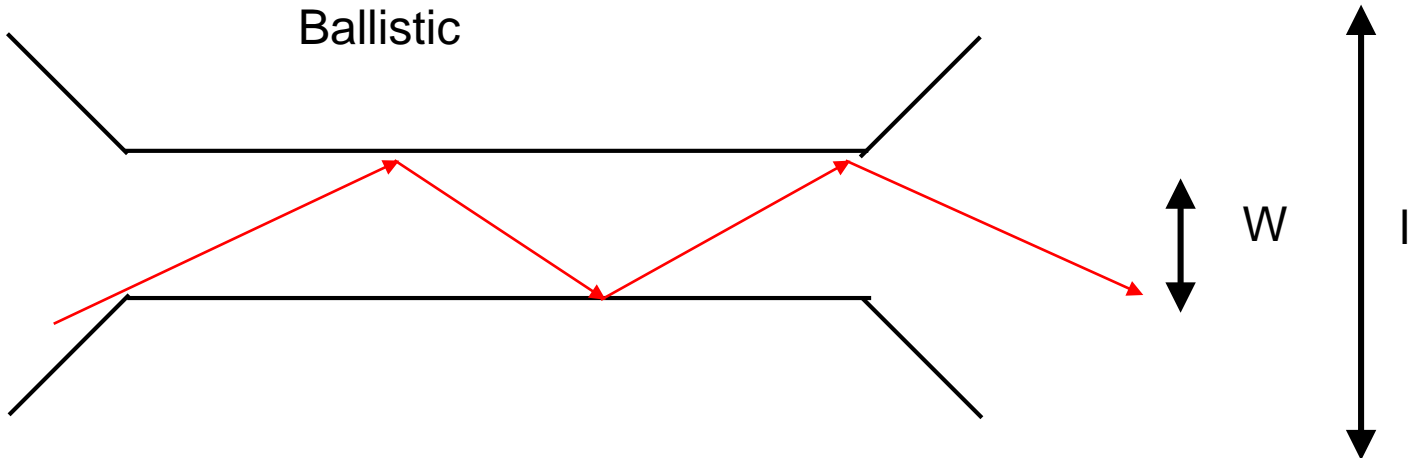## Scaling of Resistance and Electron Mean Free Path of Single-Walled Carbon Nanotubes

Meninder S. Purewal,[1] Byung Hee Hong,[2] Anirudhh Ravi,[2] Bhupesh Chandra,[3] James Hone,[3] and Philip Kim[2]
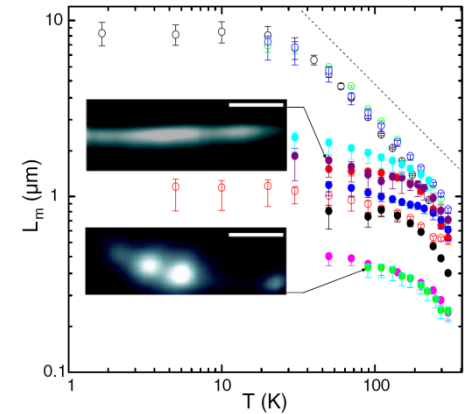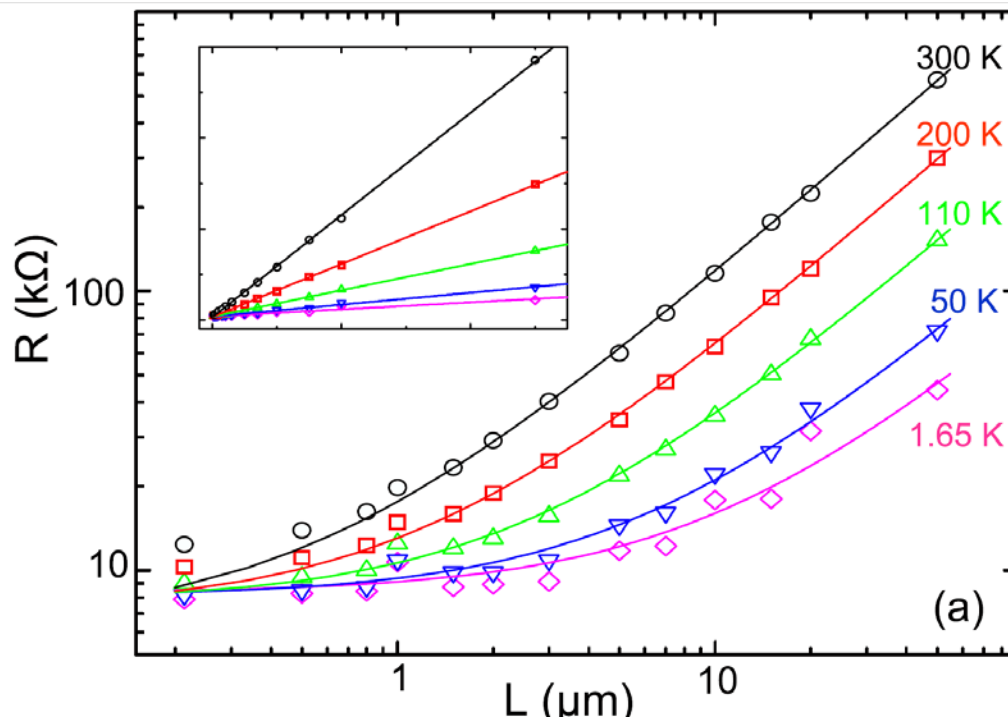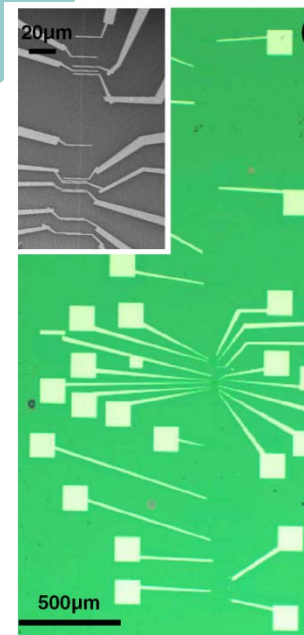
Comparison to Cu

SWNT

d=1.5 nm, 6kΩ/μm
=> 1.1 μΩ-cm
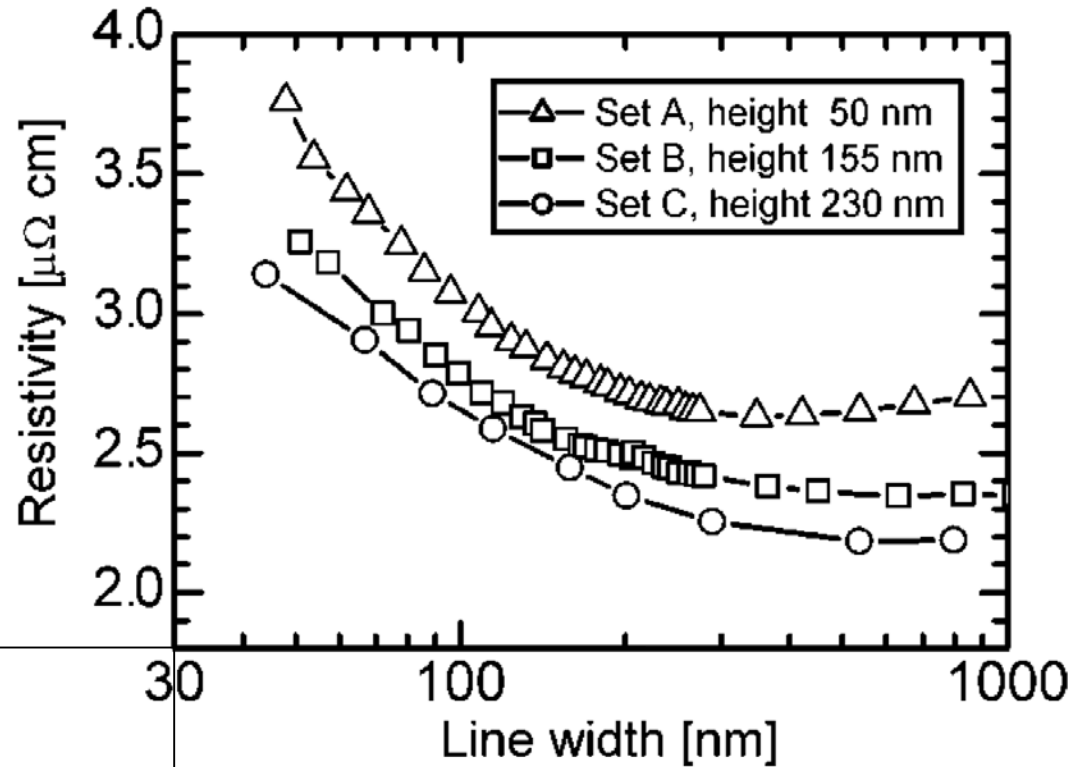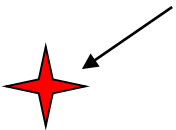
[1.] W. Steinhogl, G. Schindler, G. Steinlesberger, M. Traving and M. Engelhardt, "Comprehensive Study of the Resistivity of Copper Wires with Lateral Dimensions of 100 Nm and Smaller", *Journal of Applied Physics*, **97**, 023706, (2005).

High field transport: Diffusive regime
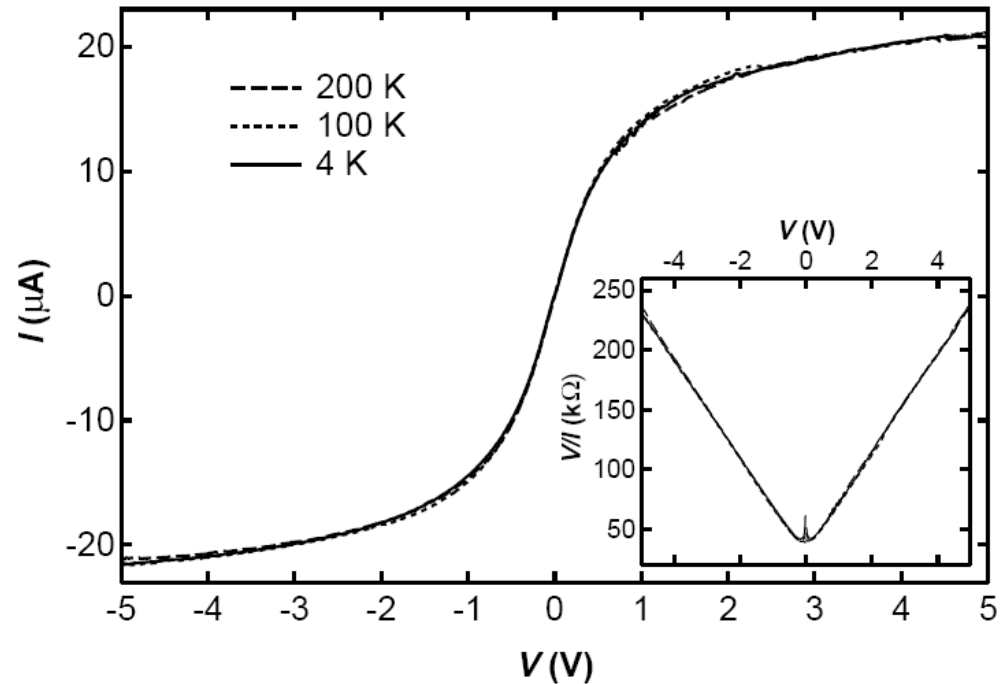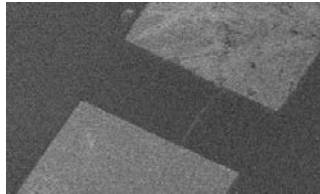
High-Field Electrical Transport in Single-Wall Carbon Nanotubes

Zhen Yao[1], Charles L. Kane[2], and Cees Dekker[1]
Phys. Rev. Lett. 84, 2941 - 2944 (2000)
[Issue 13 – March 2000]

Prior dc work:

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

Ohmic p-type contact
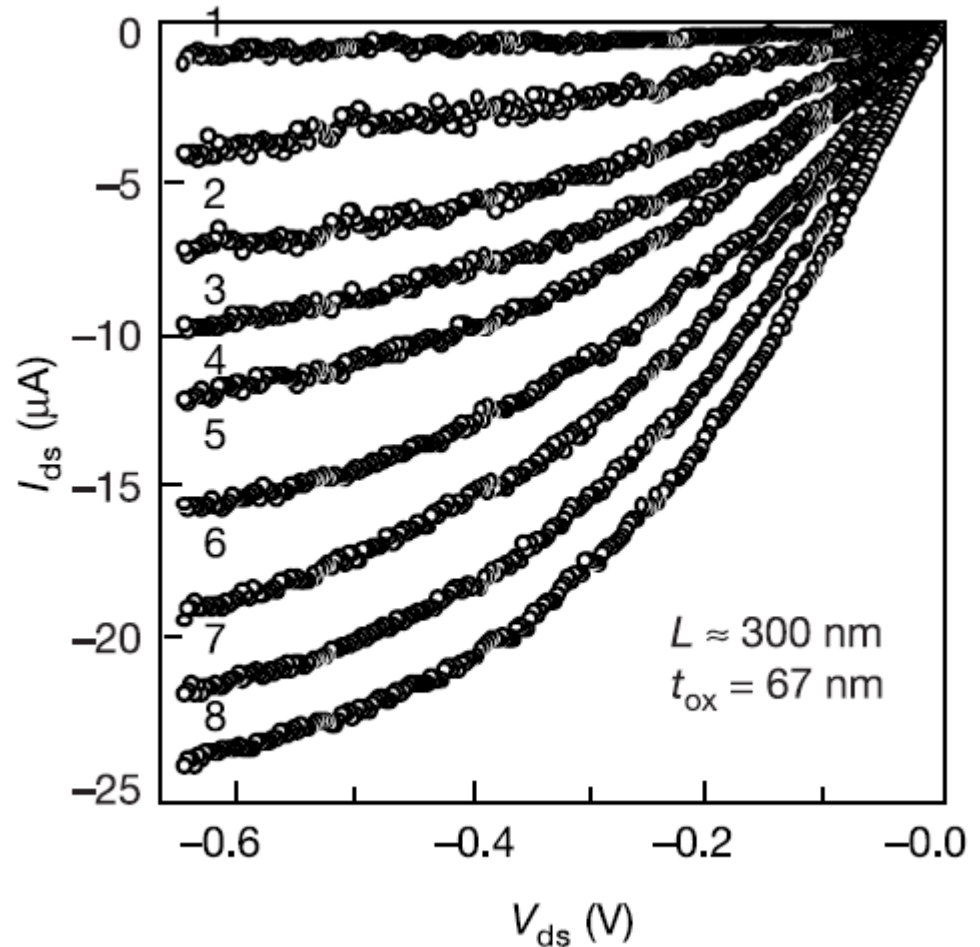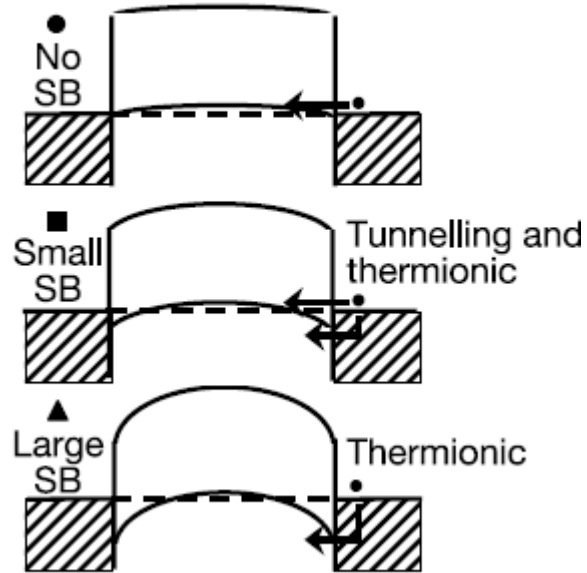
Ballistic carbon nanotube field-effect transistors

Ali Javey Jing Guo Qian Wang Mark Lundstrom & Hongjie Dai

Nature 424, 654 - 657 (2003).

EECS 277C Nanotechnology © 2017 P. Burke

Ohmic n-type contact
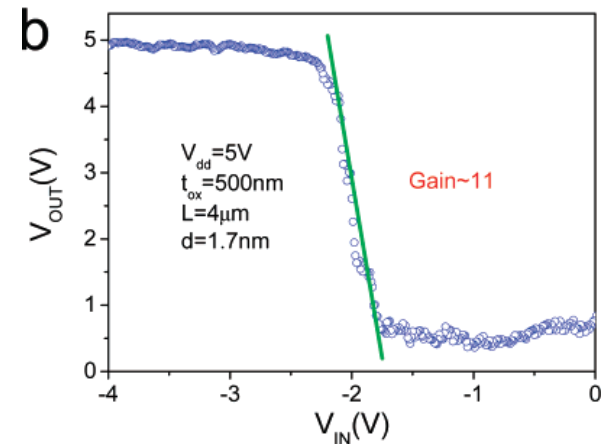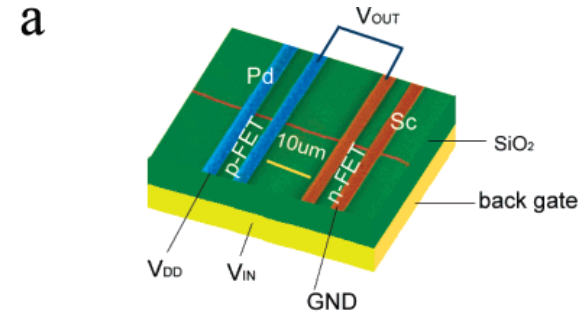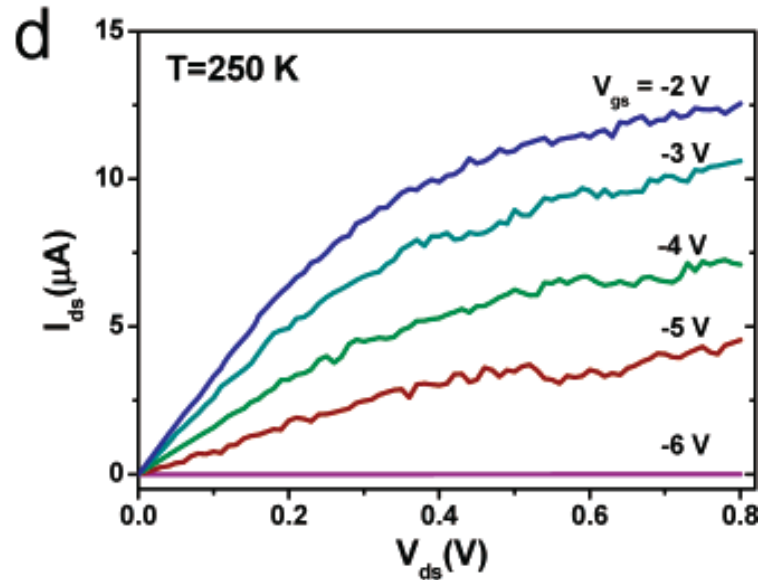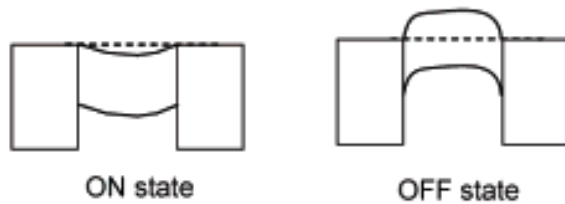
Doping-Free Fabrication of Carbon Nanotube Based Ballistic CMOS Devices and Circuits
Zhang, Z.; Liang, X.; Wang, S.; Yao, K.; Hu, Y.; Zhu, Y.; Chen, Q.; Zhou, W.; Li, Y.; Yao, Y.; Zhang, J.; Peng, L.-M.
Nano Lett.; (Letter); 2007; 7(12); 3603-3607

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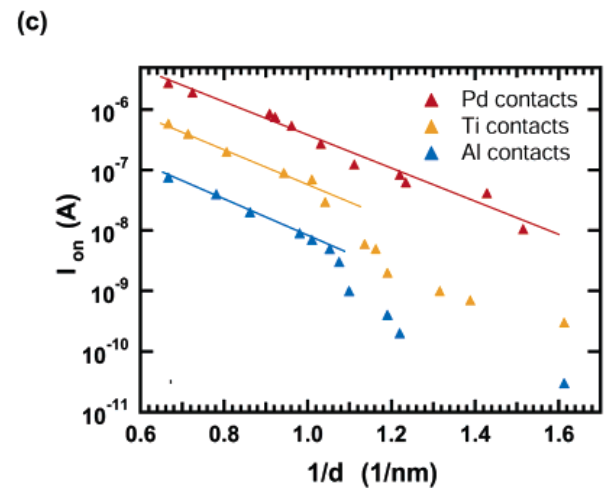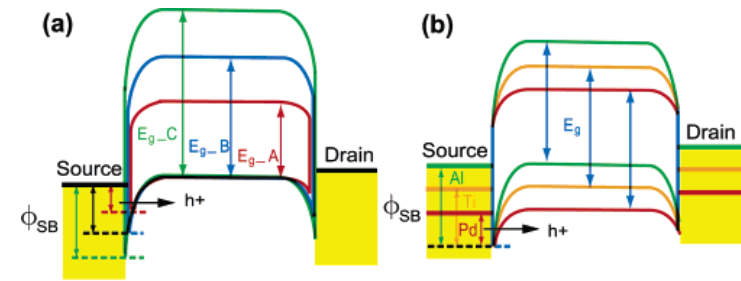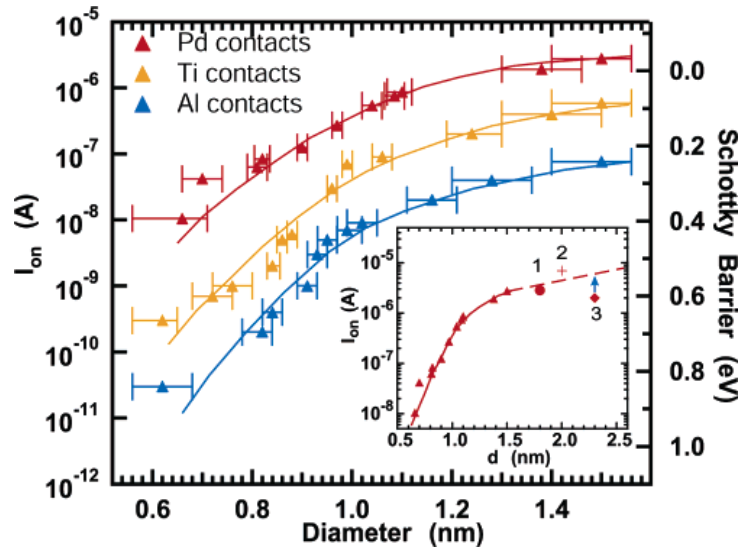
The Role of Metal-Nanotube Contact in the Performance of Carbon Nanotube Field-Effect Transistors
Chen, Z.; Appenzeller, J.; Knoch, J.; Lin, Y.-M.; Avouris, Ph.
Nano Lett.; (Letter); 2005; 5(7); 1497-1502.

N-type, p-type, SB FET

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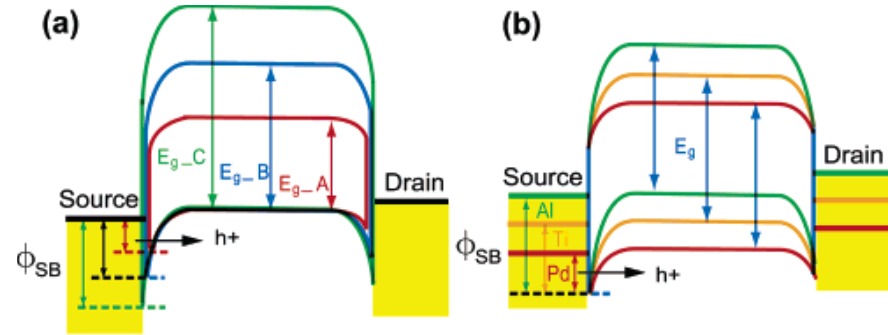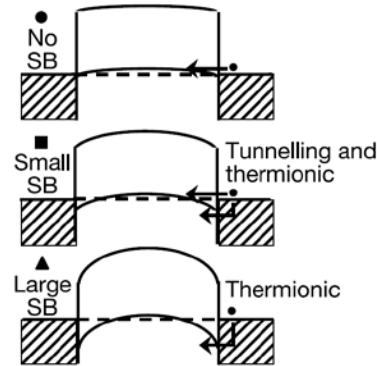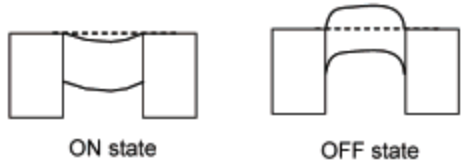
X. Peng, N. Komatsu, S. Bhattacharya, T. Shimawaki, S. Aonuma, T. Kimura and A. Osuka, "Optically Active Single-Walled Carbon Nanotubes", *Nature, **2, 361-365, (2007).***

No SB

Small SB — Tunnelling and thermionic

Large SB — Thermionic

A. Javey, J. Guo, Q. Wang, M. Lundstrom and H. J. Dai, "Ballistic Carbon Nanotube Field-Effect Transistors", *Nature, **424, 654-657, (2003).***

(a)   (b)

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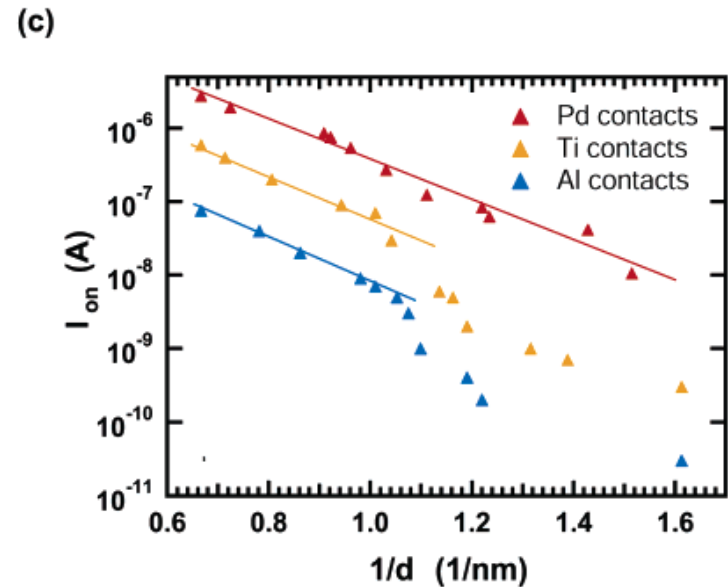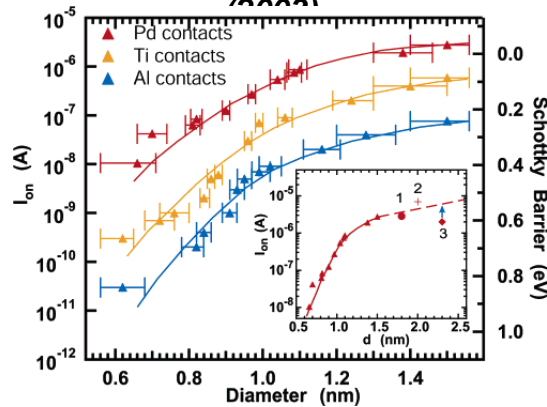
Z. Chen, J. Appenzeller, J. Knoch, Y.-M. Lin and P. Avouris, "The Role of Metal-Nanotube Contact in the Performance of Carbon Nanotube Field-Effect Transistors", *Nano Lett., **5, 1497-1502, (2005).***

Effect of parasitics

$C_{gs} \sim$ 1-10 aF
$g_m \sim$ 10 μS
$C_p \sim$ 100 aF

gate

$C_{gd,parasitic}$

$R_D = h/8e^2$
= 3 kΩ   drain

$C_{gs,parasitic}$

C_{gs}

$g_m v_{gs}$

g_d

$R_S = h/8e^2$ = 3 kΩ

source

L

gate (top)

insulator

source   drain

oxide

gate (back)

Thin film electrode

Substrate
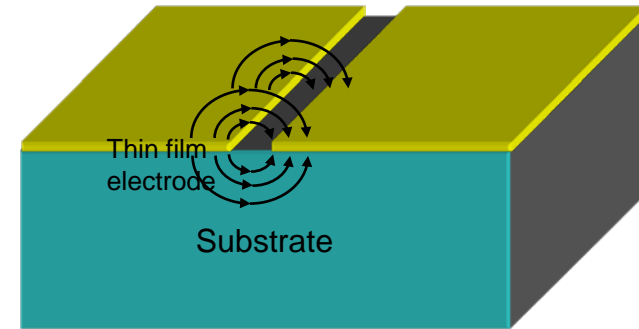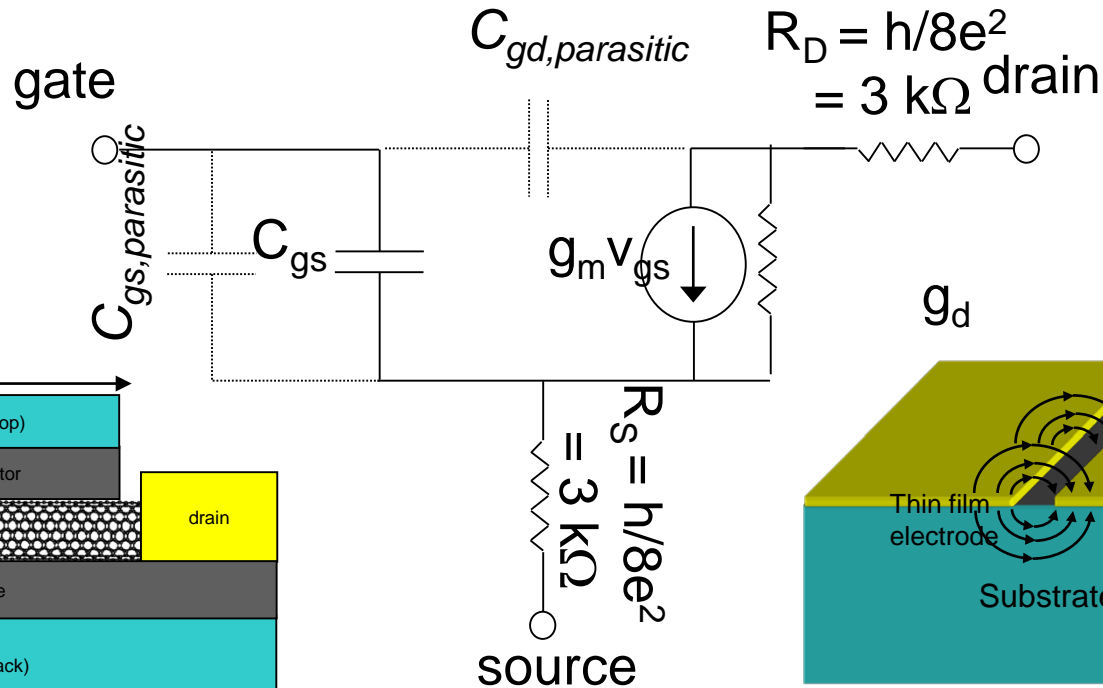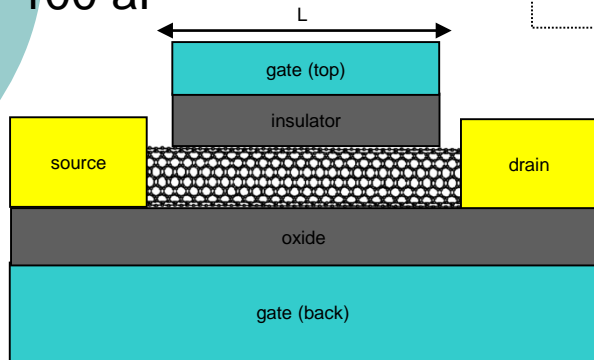
If parasitics minimized:

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

$$+ \frac{g_d}{g_m}(R_S + R_D)\left(C_{gs} + C_{gd,p} + C_{gd,p}\right)$$

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

~ 10 GHz

~ 1 THz

P. J. Burke, "AC Performance of Nanoelectronics: Towards a Ballistic THz Nanotube Transistor", *Solid State Electronics, 40, 1981-1986*

Nanotube density

a

b

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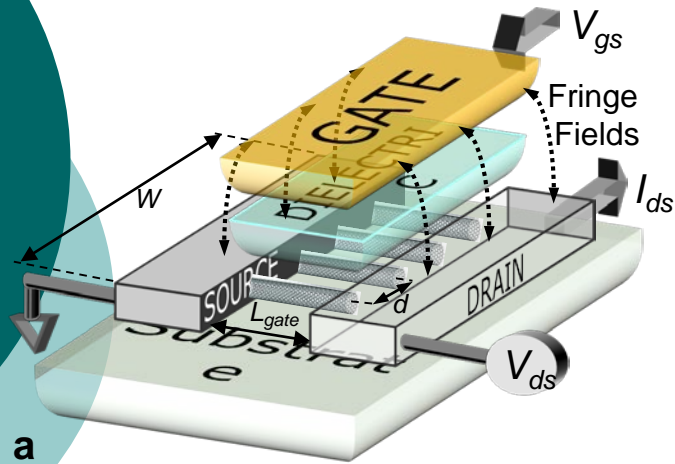
$$f_T = \frac{g_m}{2\pi C_{gs}}$$

$$f_T = \frac{g_m}{2\pi C_{gs}}\left(\frac{1}{1+\dfrac{C_W}{C_{gs}}d}\right).$$
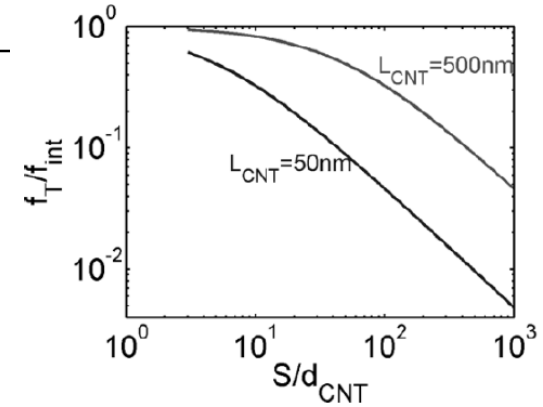
J. Guo, S. Hasan, A. Javey, G. Bosman and M. Lundstrom, "Assessment of High-Frequency Performance Potential of Carbon Nanotube Transistors", *IEEE Transactions on Nanotechnology*, **4**, 715-721, **(2005).**
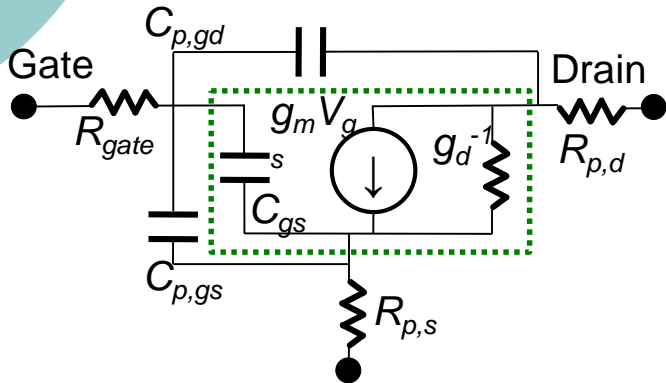
C. Rutherglen, D. Jain and P. Burke, "Nanotube Electronics for RF Applications", *Nature Nanotechnology,* in press, *(2009).*

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

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

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

1/7/2017

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).*

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L. Ding, A. Tselev, J. Wang, D. Yuan, H. Chu, T. P. McNicholas, Y. Li

Alignment: Status & Goals
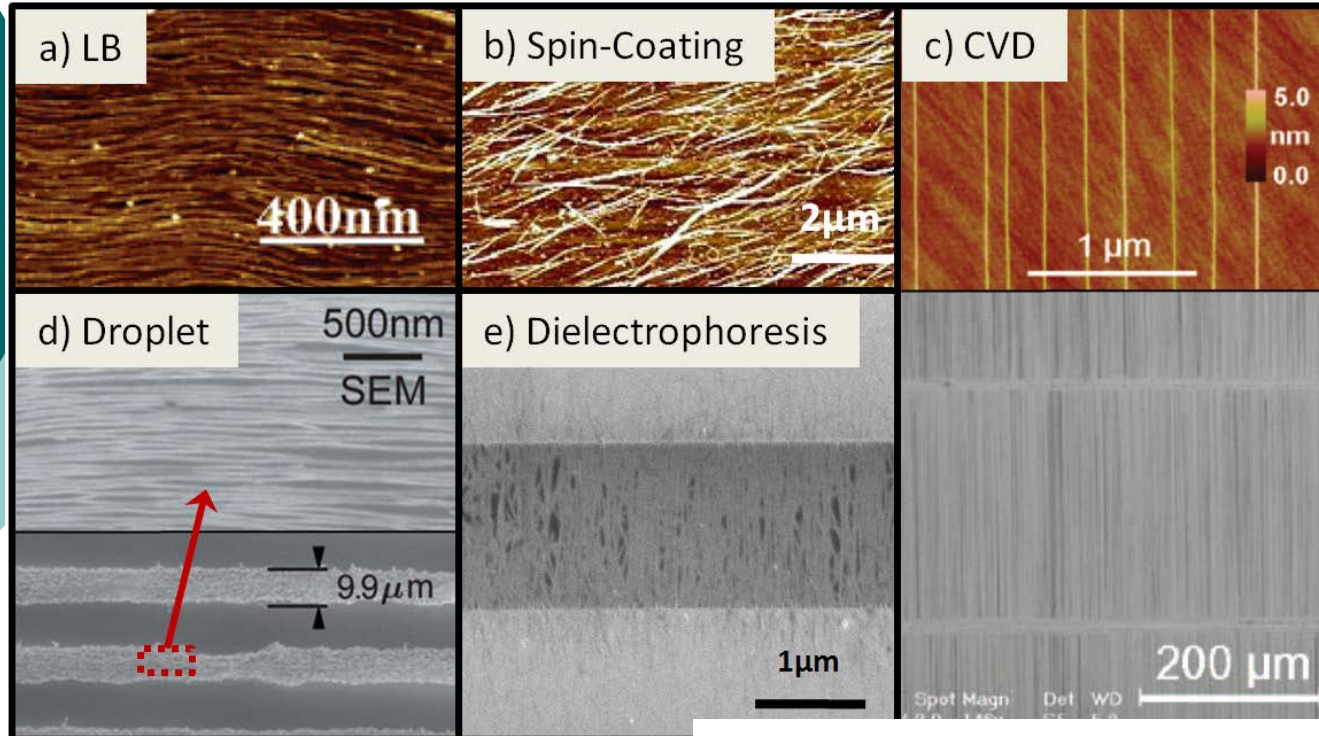
a) LB — 400nm
b) Spin-Coating — 2μm
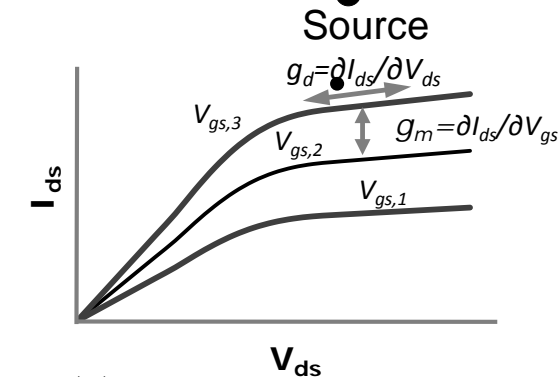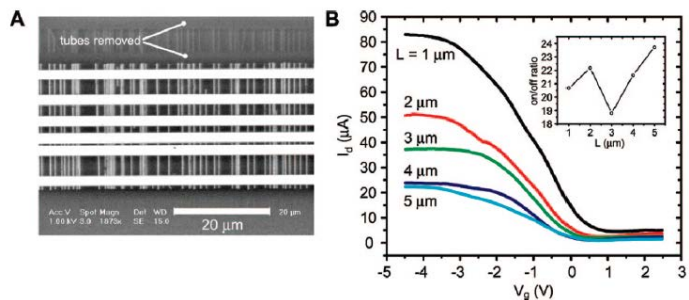c) CVD — 1 μm, 5.0 nm / 0.0
d) Droplet — 500nm SEM, 9.9μm
e) Dielectrophoresis — 1μm, 200 μm

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[107,108].
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
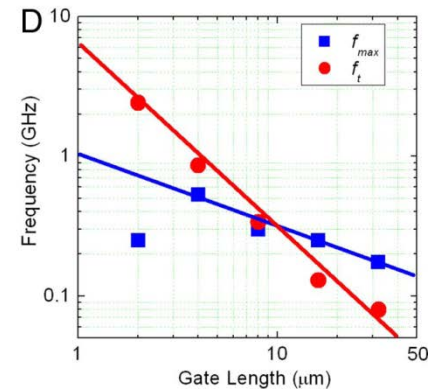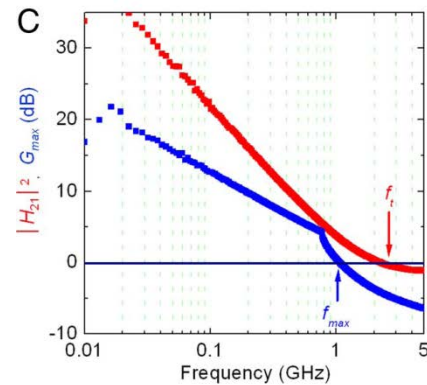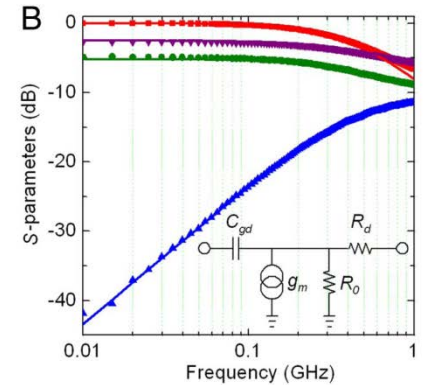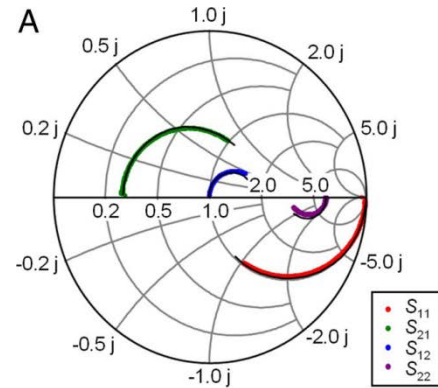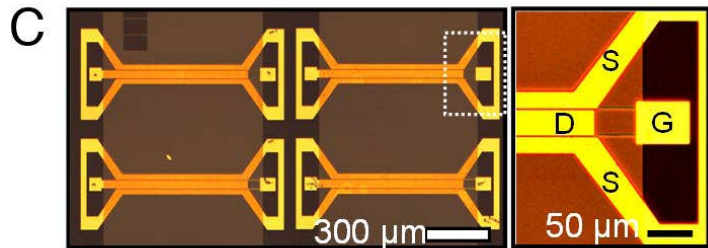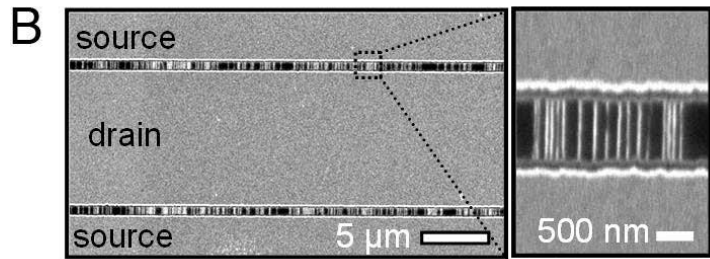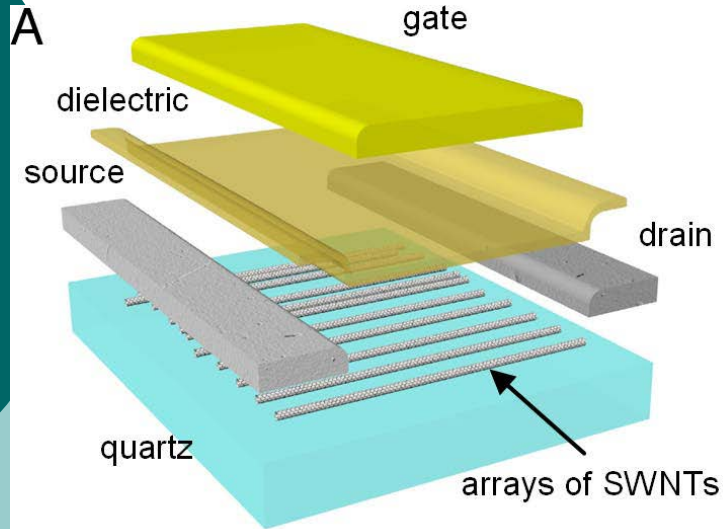
E. Cubukcu, F. Degirmenci, C. Kocabas, M. A. Zimmler, J. A. Rogers and F. Capasso, "Aligned Carbon Nanotubes as Polarization-Sensitive, Molecular near-Field Detectors", *Proceedings of the National Academy of Sciences of the United States of America, **106,** 2495-2499, **(2009).***

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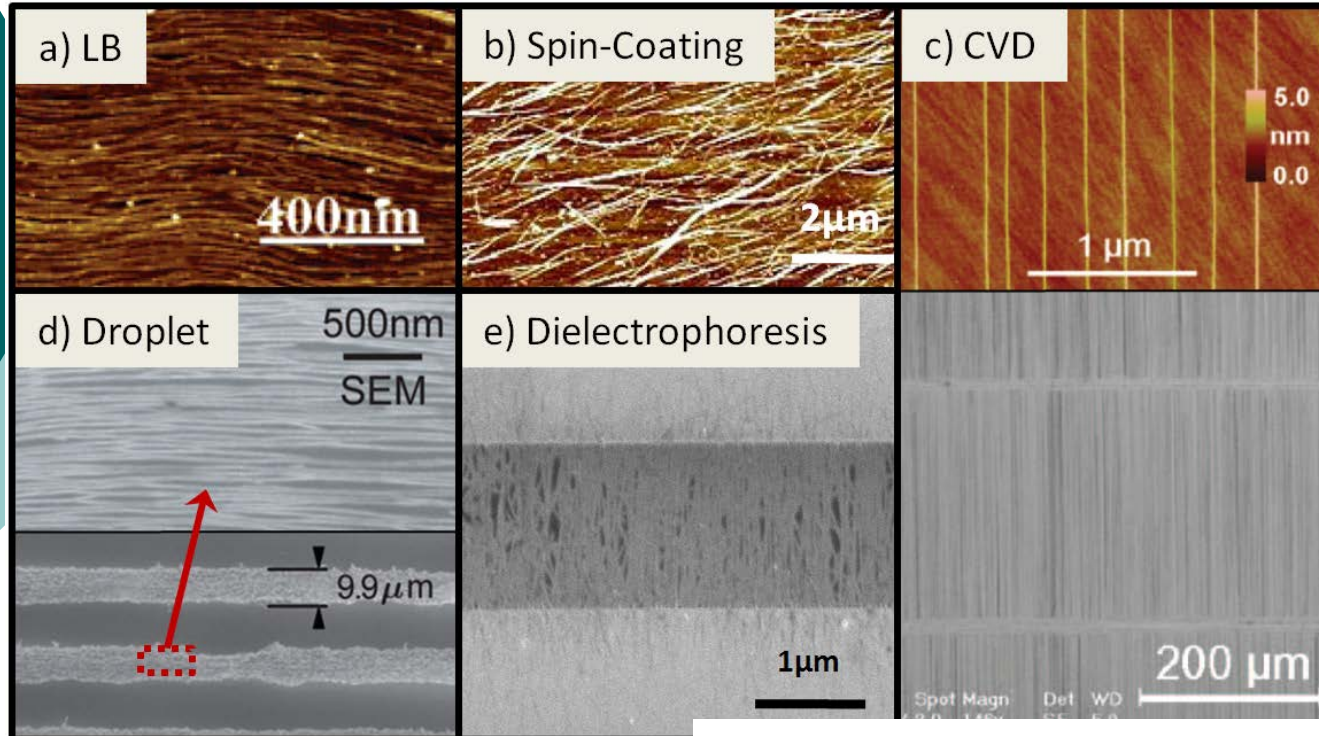
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Mobilities
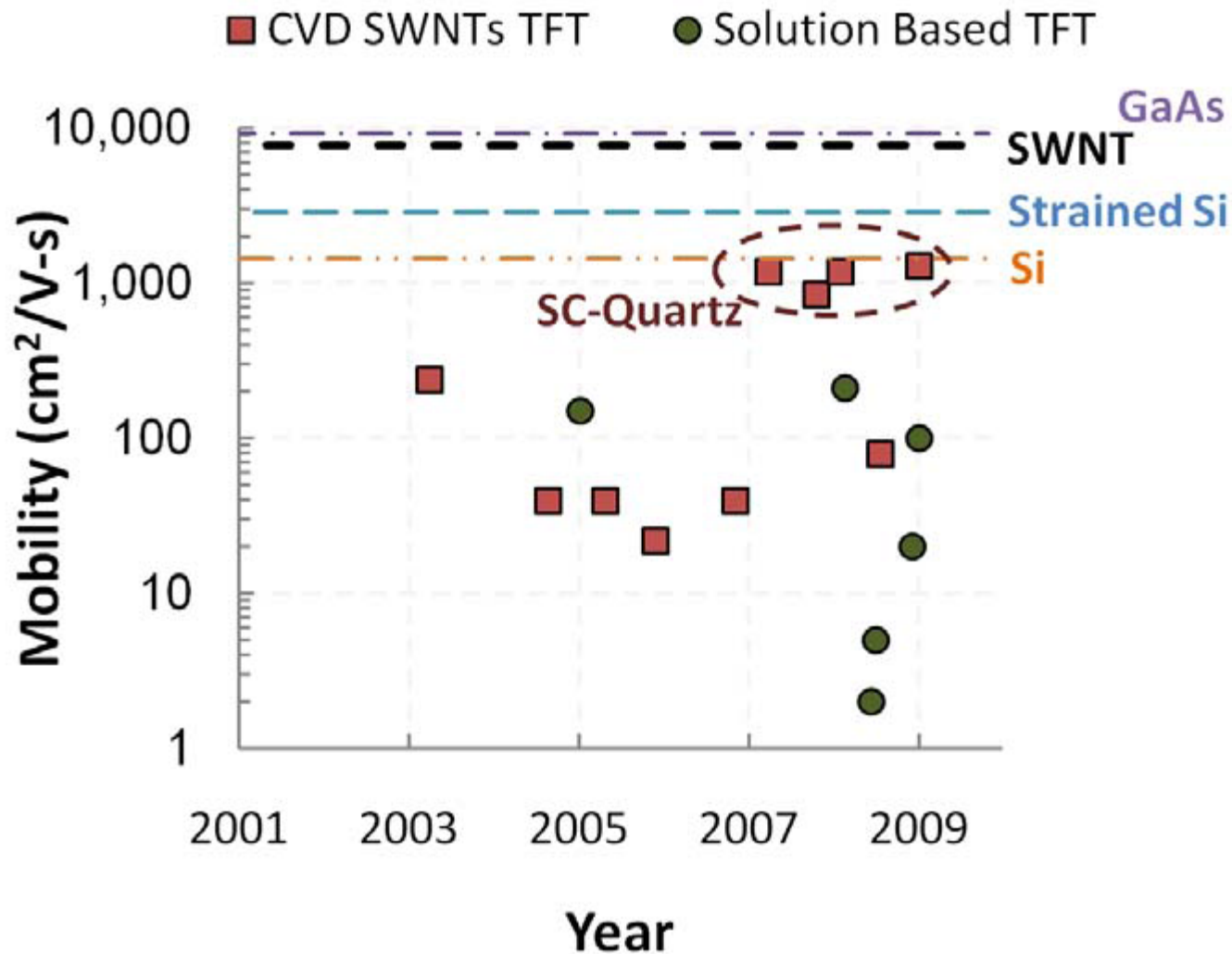
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EECS 277C Nanotechnology © 2017 P. Burke

(n,m) enrichment
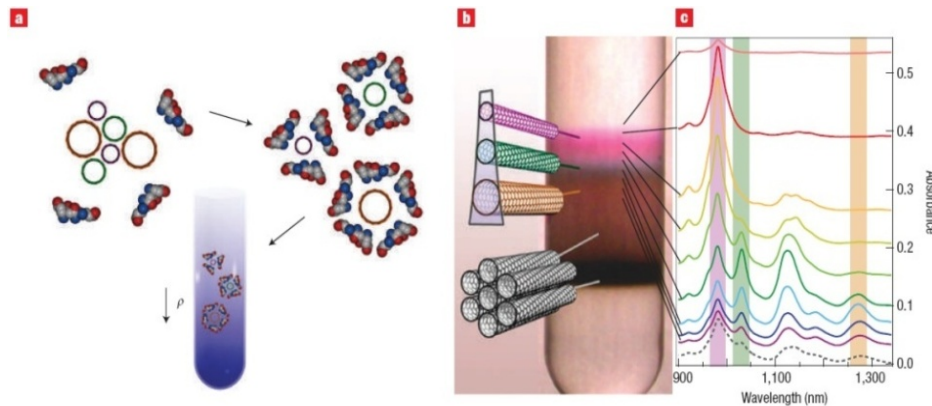
● CNTs are surfactant encapsulated and separate by density during centrifugation
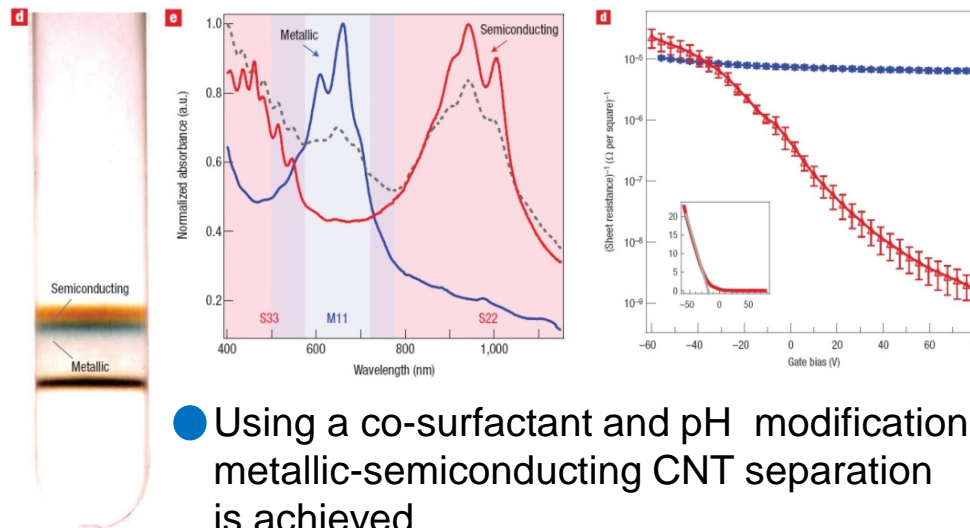
● Using a co-surfactant and pH modification, metallic-semiconducting CNT separation is achieved

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

Applications: Low Cost- RFID
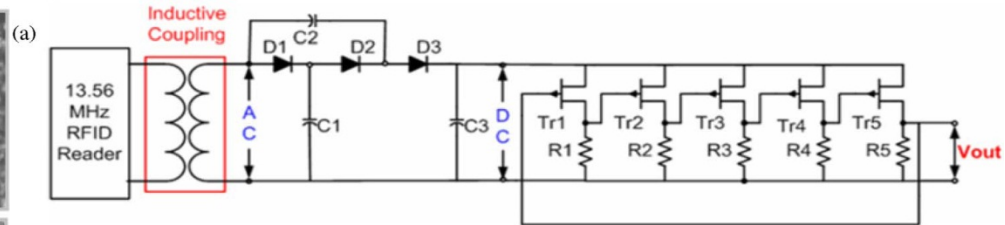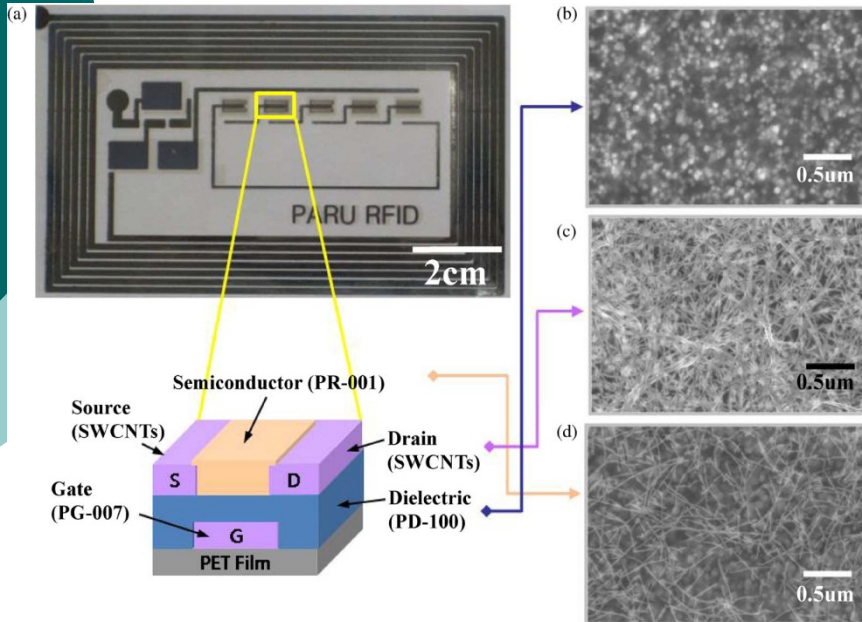
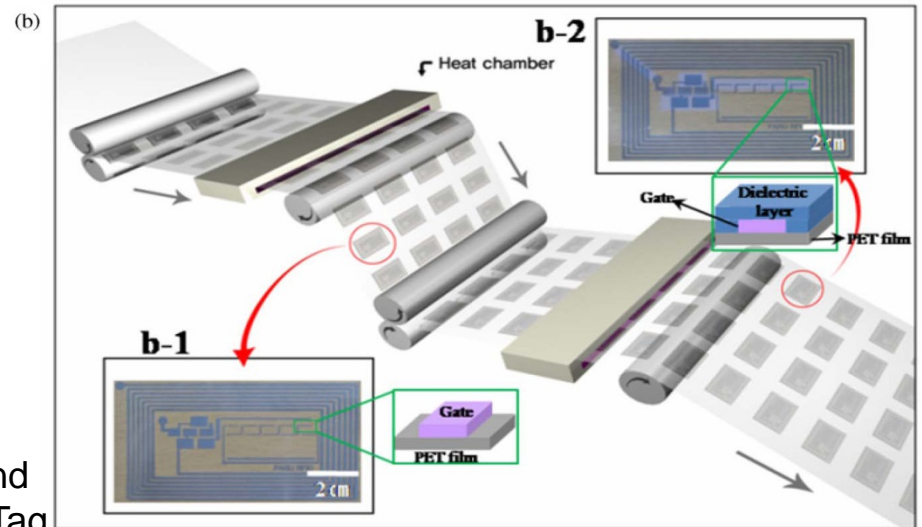Mob ~ 5 & on/off ratio 100

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?

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burkegroup 1.0kV 13.2mm x250 3/5/08   200um

(n,m) enrichment

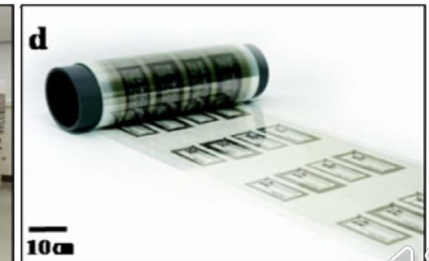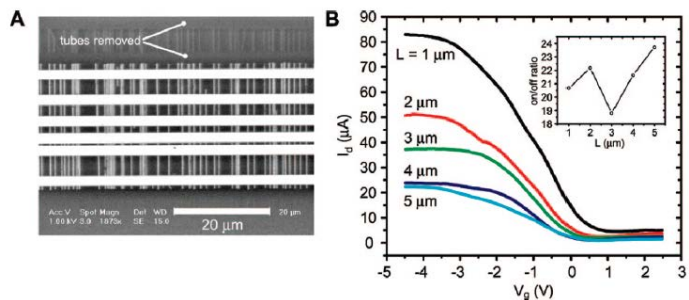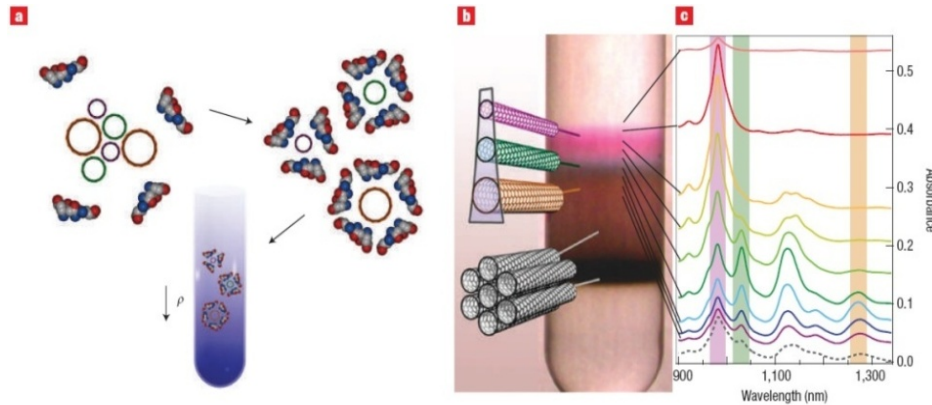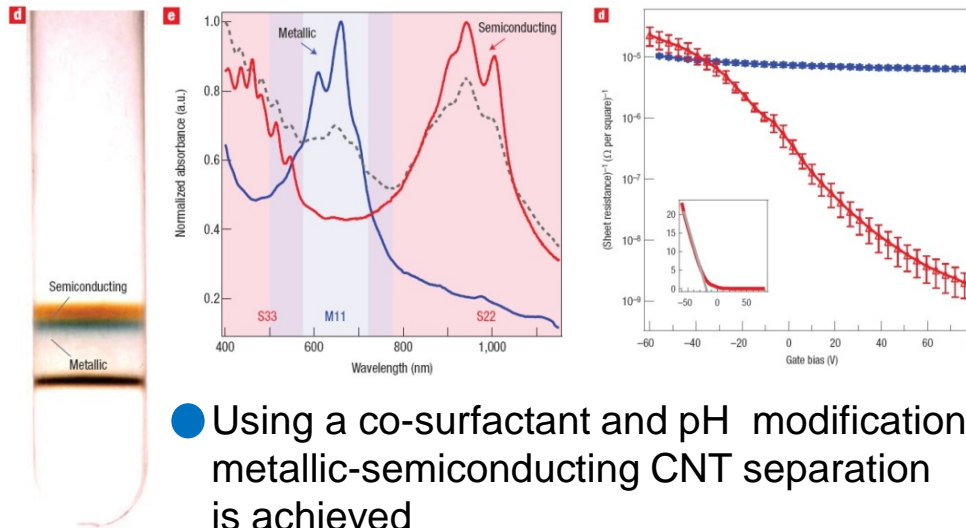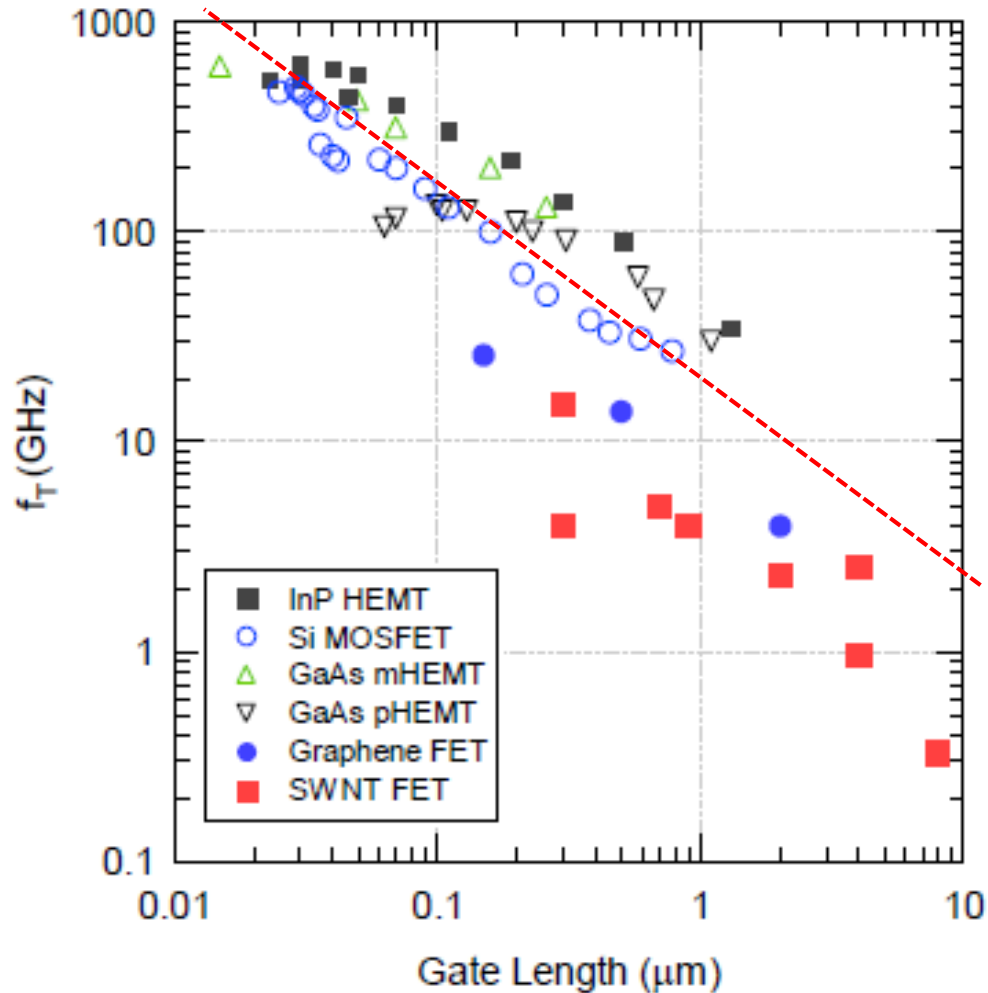- CNTs are surfactant encapsulated and separate by density during centrifugation

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Comparison to other semiconductors

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

Graphene (Kim)
0.5 to 5x that value

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