Carbon Nanotube Interconnects

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and MARCO Interconnect Focus Center

Transistor and Interconnect Scaling

Transistor Scaling:

- Faster devices
- Lower energy per binary switching operation
- More functionality

Interconnect Scaling:

Constant capacitance per unit length

$$R_{\text{int}} C_{\text{int}} \propto \rho \varepsilon_r l^2 / WT$$

Within-macrocell interconnects

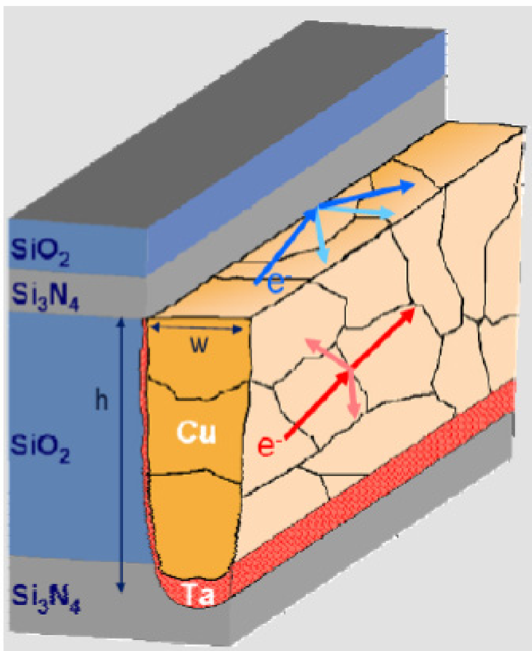
- Length scales with technology
- Must scale ε_r to scale RC product

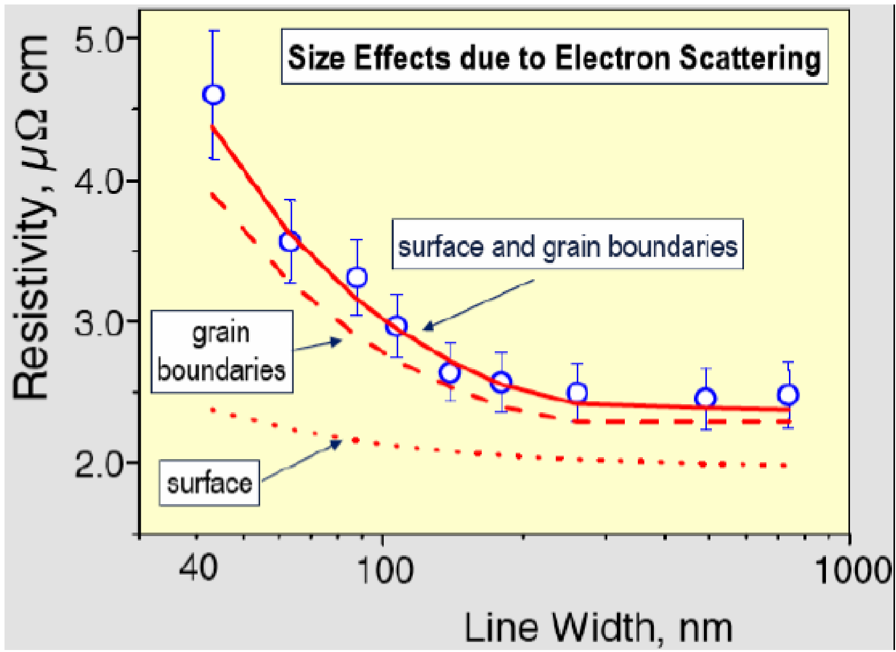
Between-macrocell interconnects:

- Length does not scale
- Growing RC delay
- Reverse scaling
- Many power-hungry repeaters needed

Up to 70% of on-chip capacitance in high-performance chips is due interconnects.

Copper Resistivity





Copper resistivity increases as cross-sectional dimensions scale.

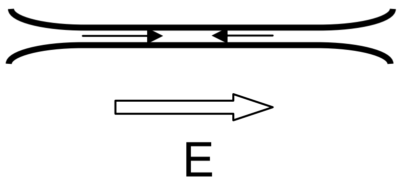
No known technology solution to this problem [2].

[1] W. Steinhögl, et al., *Physical Rev. B*, Vol. 66, 075414 (2002).

[2] Sematech/Novellus Copper Resistivity Workshop, June 2005.

Carbon Nanotubes: Potential Solution

1-D conductors:

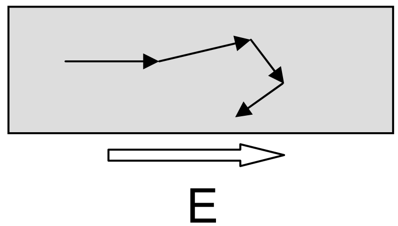


Quantum Wires:

Very limited phase space for scattering

Mean free paths as large as 1.6μm

3-D conductors:



Conventional wires :

Backscattering through a series of small angle scatterings.

Mean free paths ~ 30nm.

Best example: Carbon Nanotubes

Large Mean free paths

Strong carbon bonds

2 orders of magnitude larger current density

Both metallic and semiconductor

Research Objectives

Large mean free paths and large current densities

Potential candidates for interconnects for nanoelectronics

Quantify physical limits:

1. Determine whether they can ever outperform copper wires
2. Determine the promising applications
3. Develop guidelines for their development

Outline

- Circuit Models SWNTs and MWNTs
- Local Interconnects
- Semi-global & Global Interconnects
- Conclusions

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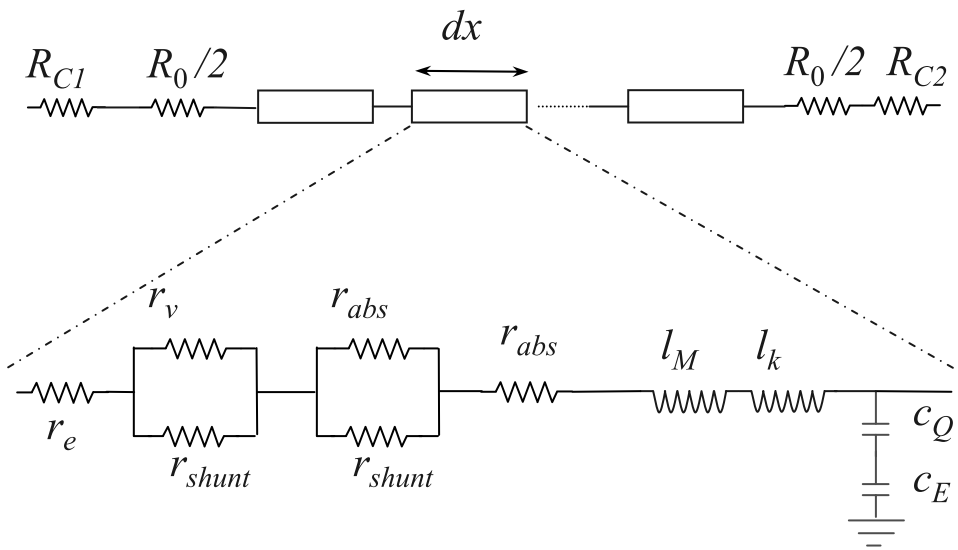
The Complete Circuit Model for CNTs



$$r \approx \frac{R_0}{10^3 D}\left(\frac{T}{T_0} - 2\right), \quad T_0 = 100K$$

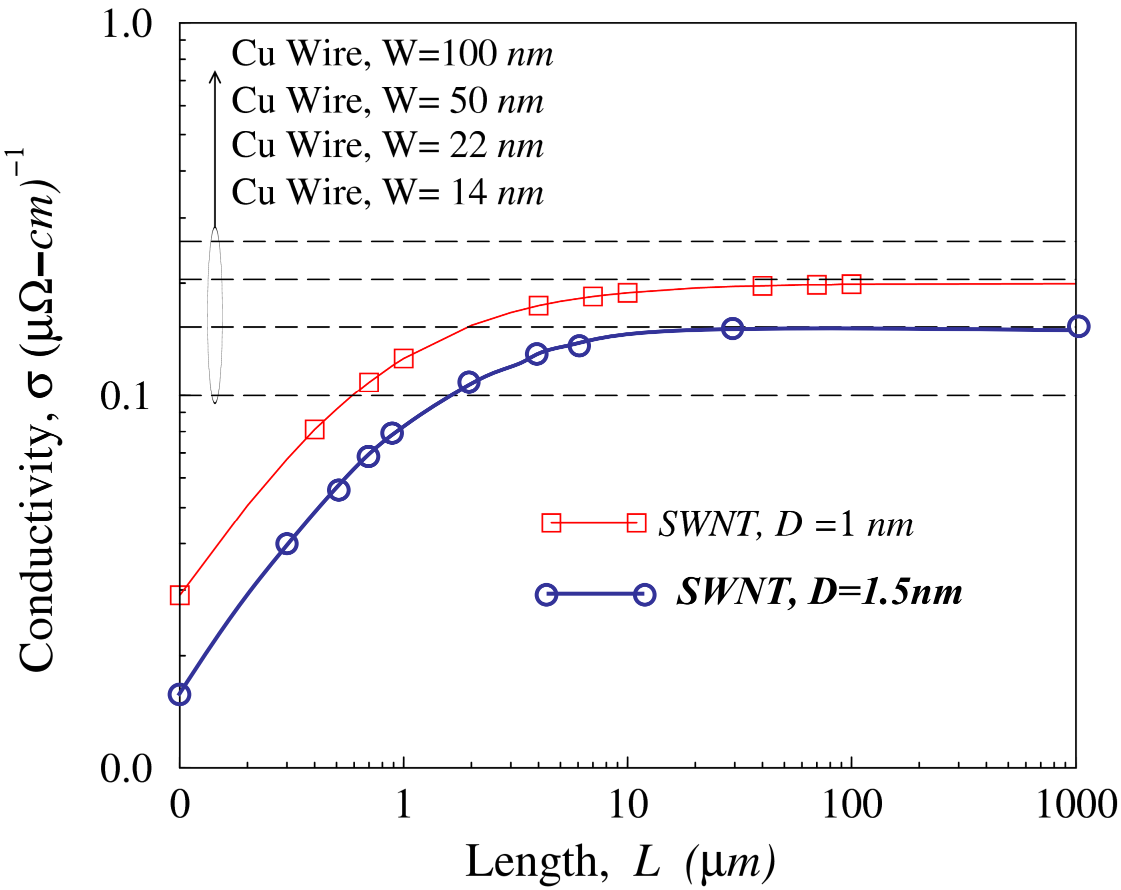
$$\ell_{eff} \approx \frac{10^3 D}{T / T_0 - 2}$$

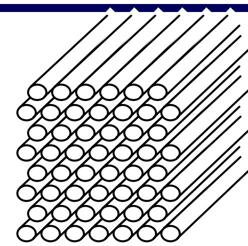
Circuit model for a graphene tube with diameter *D* @ temperature *T*.

The effective mean free path increases linearly as diameter increases.

A. Naeemi and J. Meindl, *IEEE Electron Device Letters*, vol. 28, pp. 135-138, 2007.

Conductivity of SWNT-Bundles





T=100^{0}C

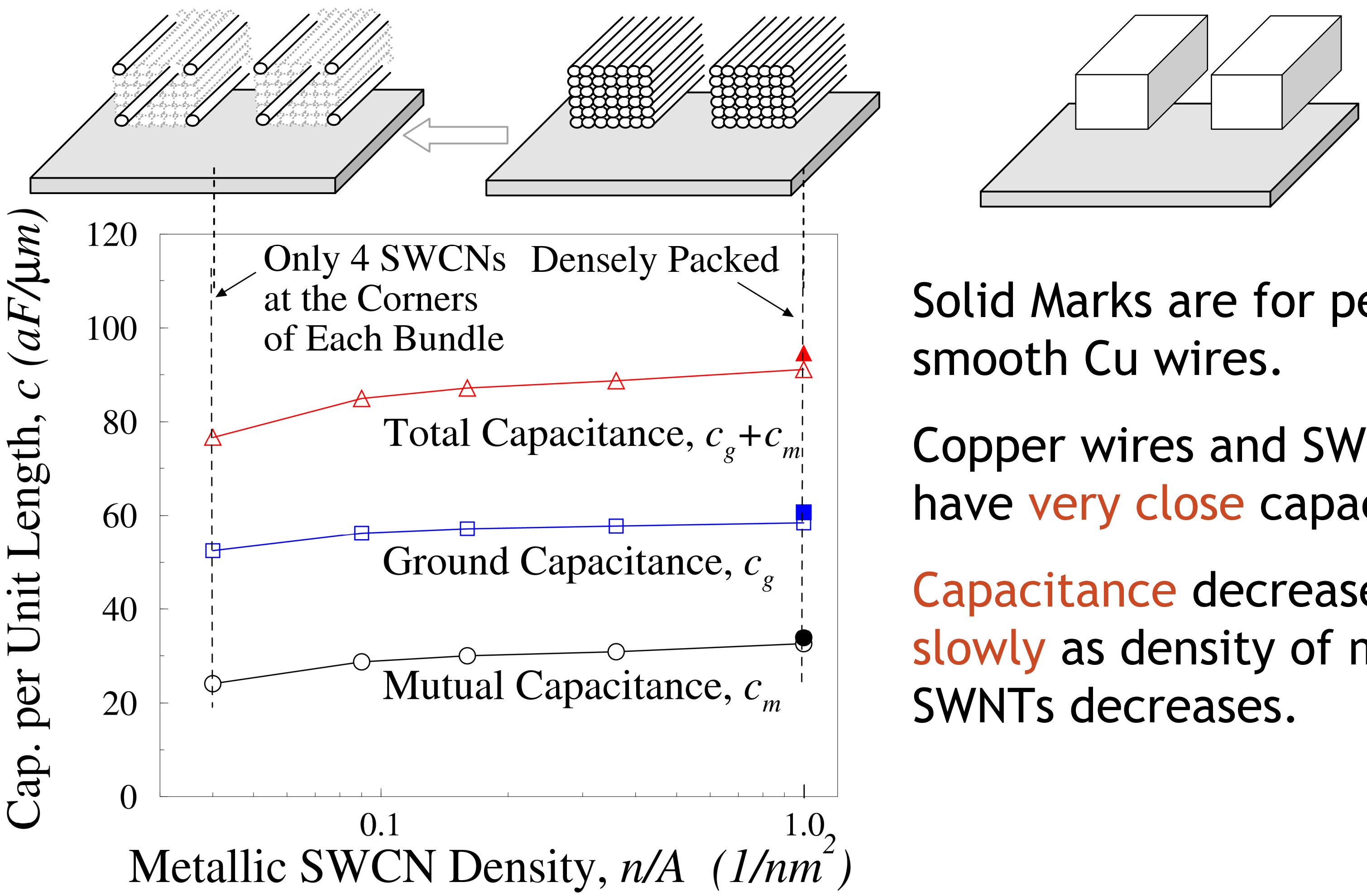
Random Chirality

0.34*nm spacing*

$R_C << RQ$

1/3 of SWNTs are metallic if chirality is random.
Conductivity of SWNT-bundles decreases as diameter increases or length decreases.

Capacitance of SWNT-Bundles

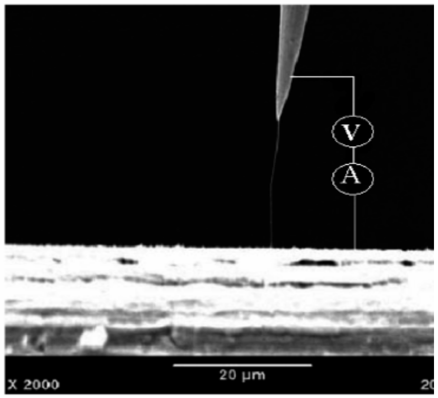


Solid Marks are for perfectly smooth Cu wires.

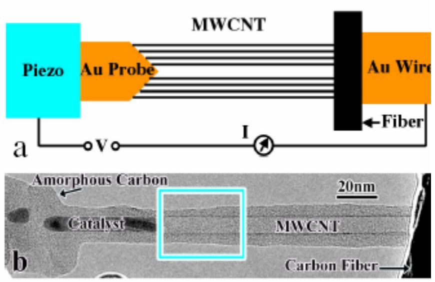
Copper wires and SWNT bundles have very close capacitances.

Capacitance decreases very slowly as density of metallic SWNTs decreases.

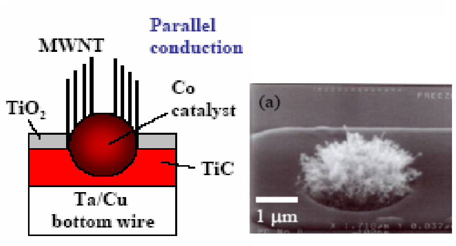
Multi-Wall Carbon Nanotubes



[*]



[**]



[***]

Initial experiments involved side contacts.

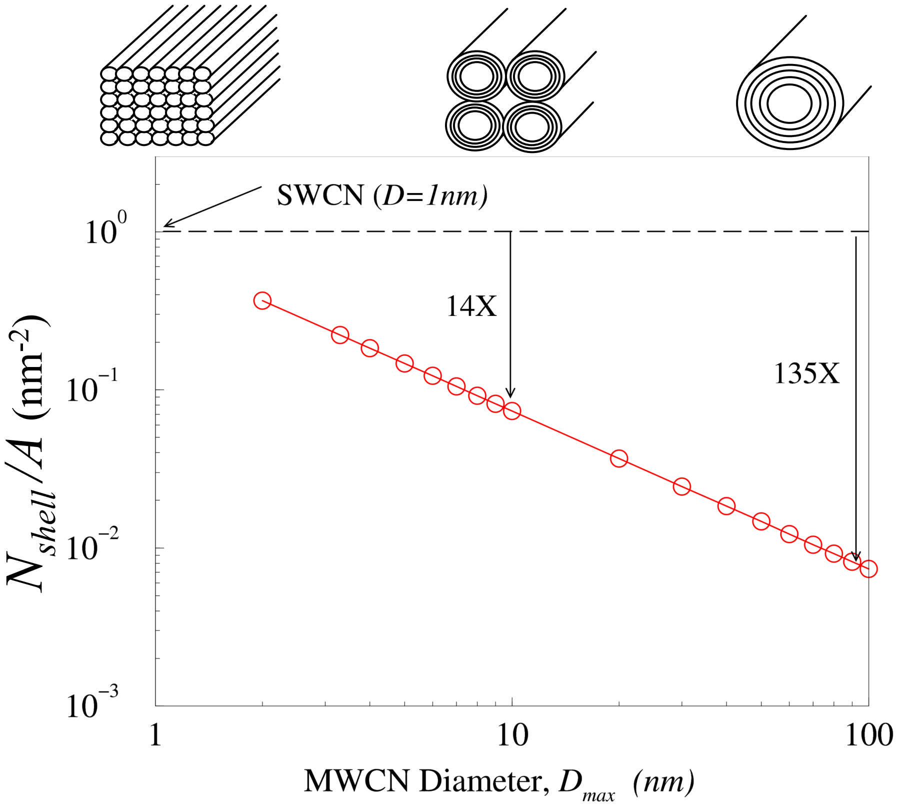
Due to weak inter-shell coupling only outer shells conducted.

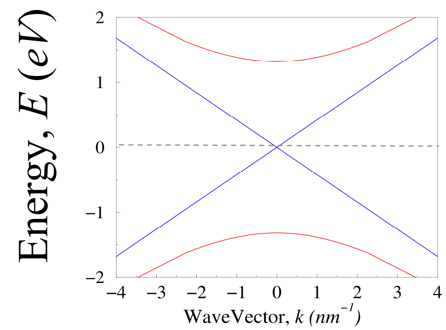
Recent experiments and models have confirmed that all shells can conduct if properly connected to contacts.

Question: Can MWNTs potentially outperform Cu or even SWNT-bundles?

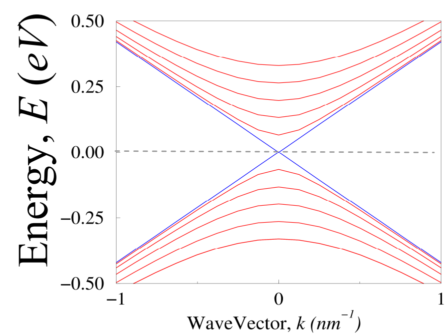
[*] H. J. Li, et al., *Physical Review Letters*, **95**, 086601 (2005).
[**] J. Y. Huang, et al., *Physical Review Lett.*, **94**, 236802 (2005).
[***] M. Nihei et al., *IEEE IITC*, pp. 234-236, 2005.

Number of Channels per Area





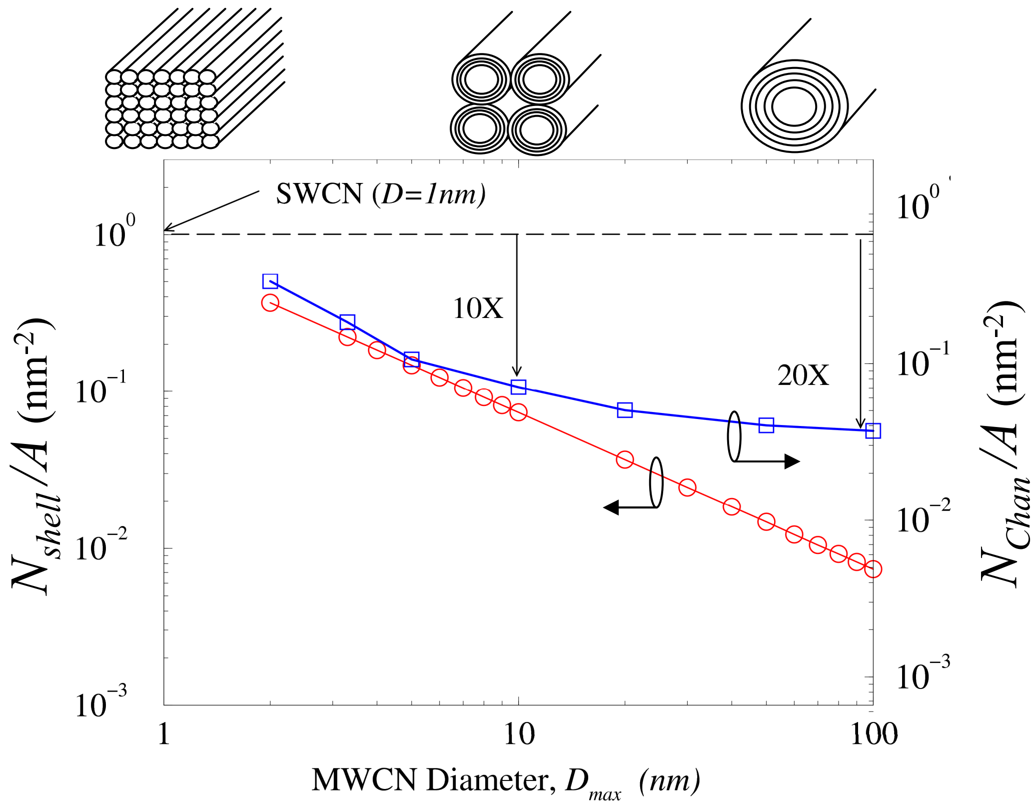
Metallic,
D =1*nm*

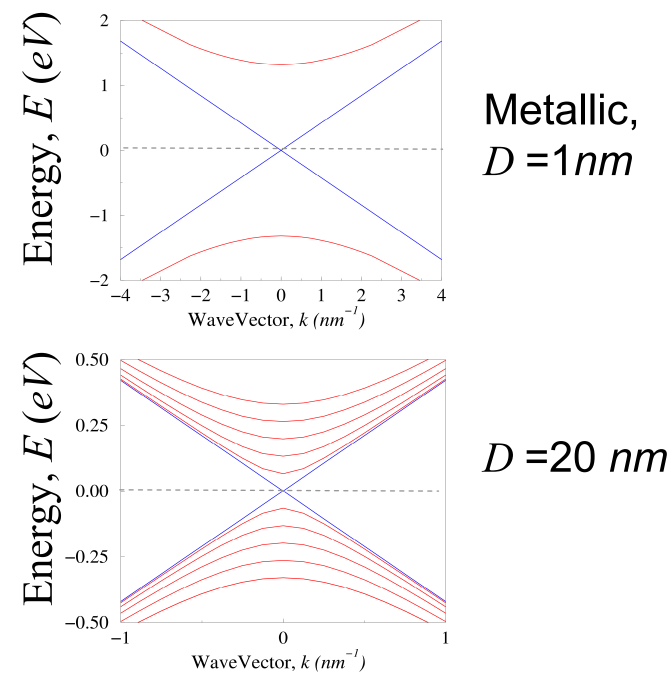


D =20 *nm*

# of shells per area drops rapidly as *D* increases.

Number of Channels per Area

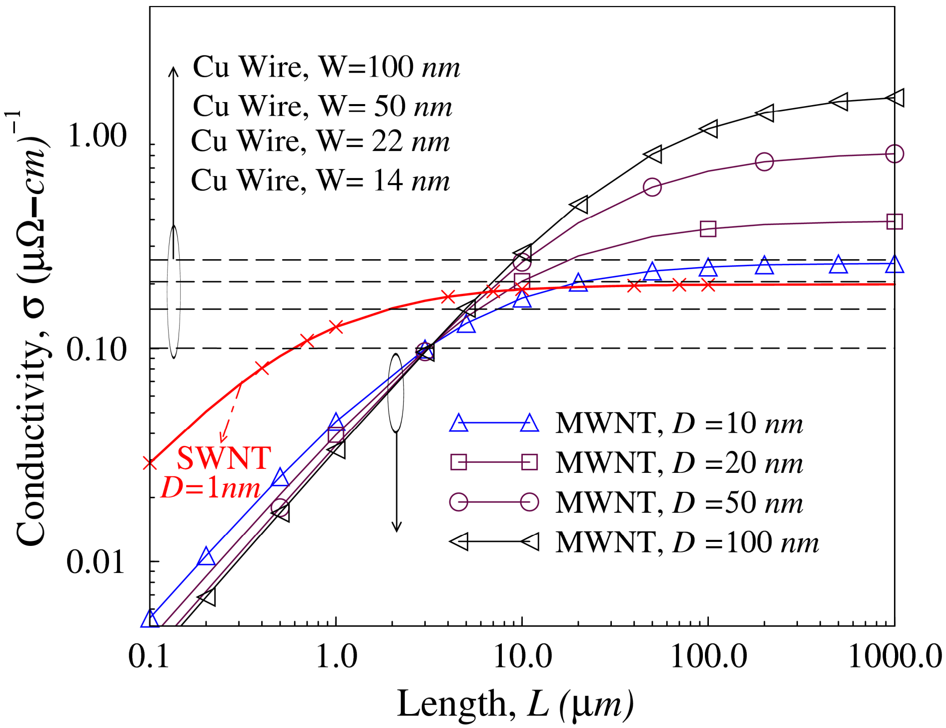


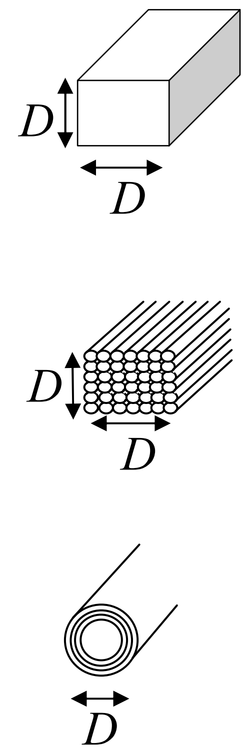


The increase in the # of channels per shell is not enough.

The MFP increases linearly with diameter as long as the level of the real disorder remains constant.

Conductivity of MWNTs



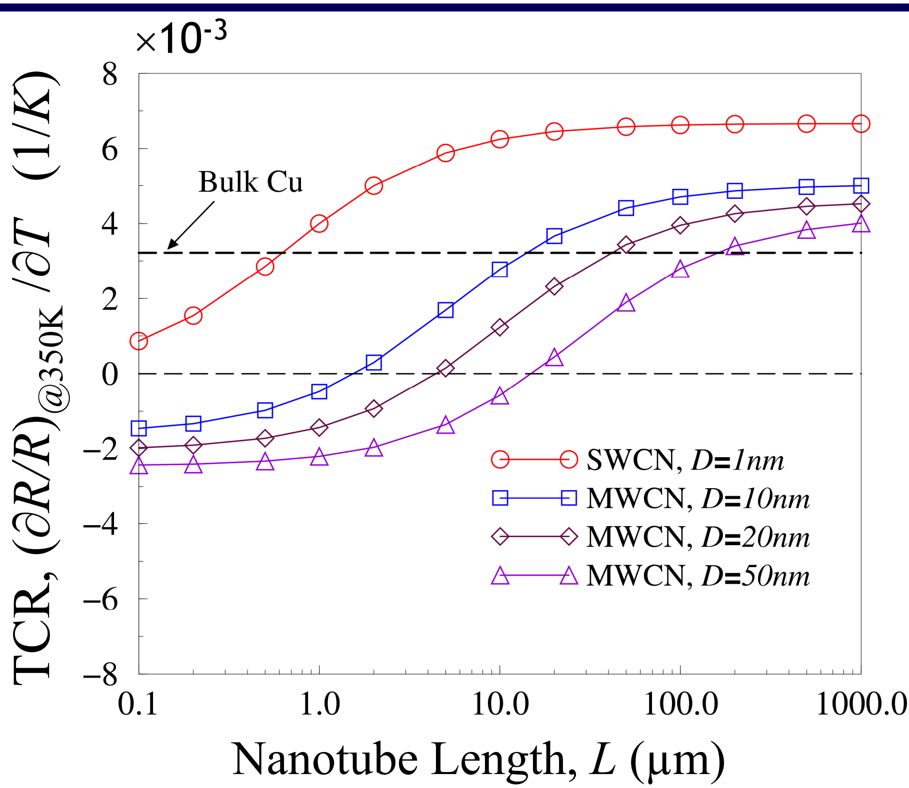


For large lengths large MWNTs offer the highest conductivity.

For mid-range lengths SWNT-bundles offer the highest conductivity.

A. Naeemi and J. D. Meindl, *IEEE Electron Device Letters*, pp. 338-340, May 2006.

Temp. Coefficient of Resistance (TCR)



$$R = R_{@350K}[1 + TCR(T - 350K)]$$

Two opposing mechanisms when temperature rises

- Increase in electron-phonon scatterings
- Increase in the number of conduction channels

Unique devices whose TCRs vary from negative to positive values

A. Naeemi and J. Meindl, *IEEE Electron Device Letters*, vol. 28, pp. 135-138, 2007.

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Local Interconnects: $R_{int} < R_{tr}$

Resistance dominated by transistors whereas capacitance is dominated by interconnects.

An interconnect roughly 10 gate pitch long has a capacitance comparable to a typical gate.

An interconnect roughly a few hundred gate pitch long has a resistance comparable to a typical gate.

A major source of power dissipation.

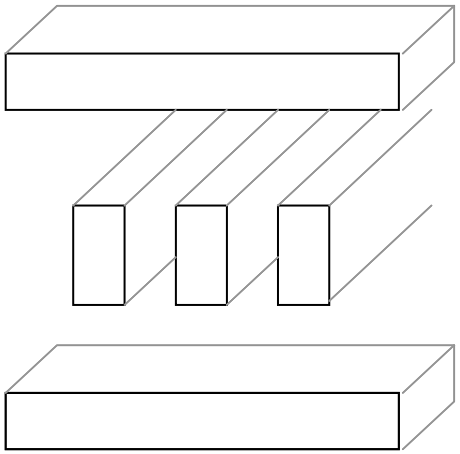
Aspect Ratio

Aspect ratios as large as 1.5 to 2.5 are used to avoid electromigration.

Increase latency, crosstalk, power dissipation and dynamic delay variation.

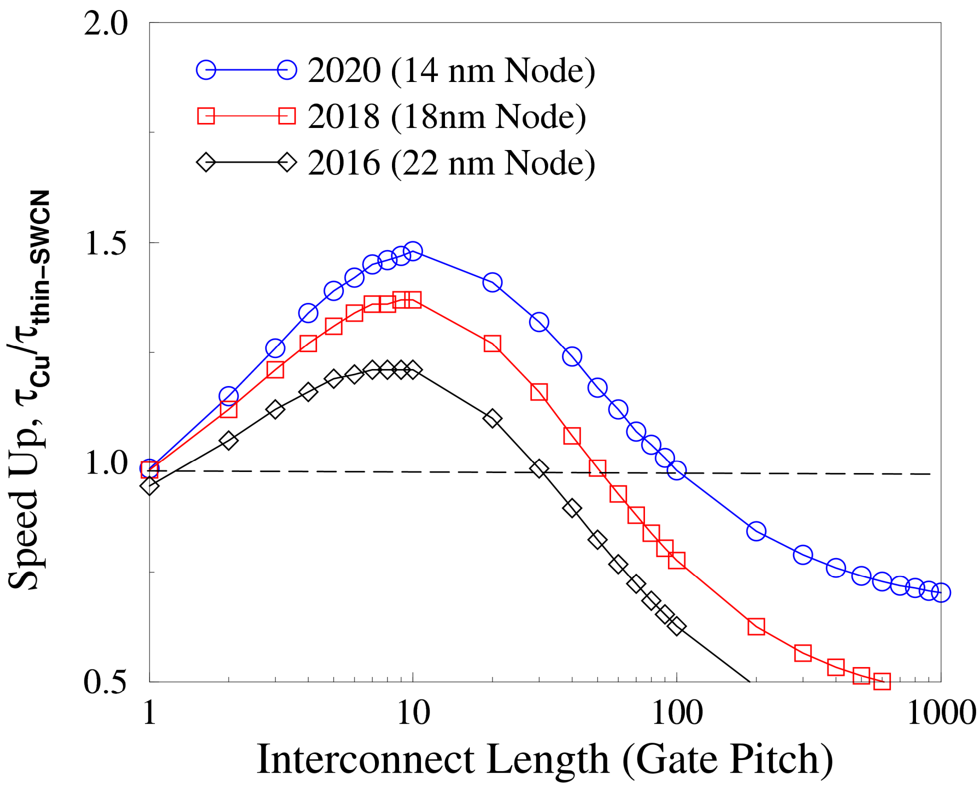
Thickness variations caused by CMP exacerbate the problem.

70% of the total capacitance of a high-performance chip is due interconnects most of which due to local interconnects [*].

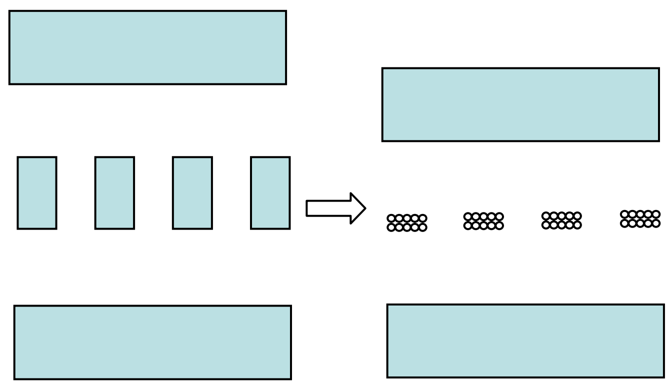


[*] T. Sakurai, *IEEE ISSCC Dig, Tech*. Papers, pp. 26-29, 2003.

Thin SWNT Signal Interconnects



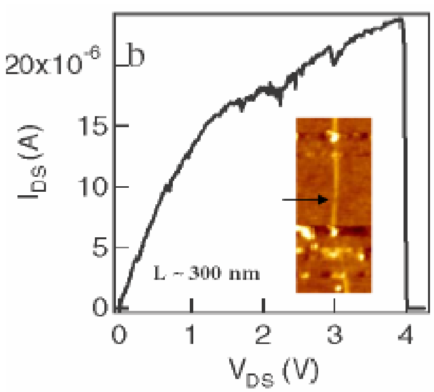
R_C =3.5KΩ
1/3 metallic
T=100^{0}C
0.34nm separation
Bi-layer SWNT Interconnects
Worst-case delay considered



4x smaller lateral capacitance, 2.7x smaller worst-case capacitance
2x smaller average capacitance

2x lower dynamic power dissipation

Contacts for Thin SWNT Interconnects



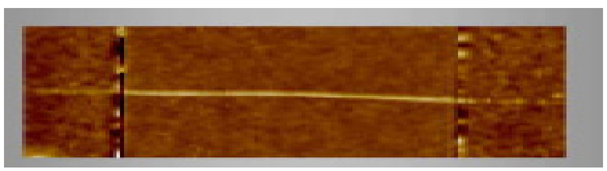
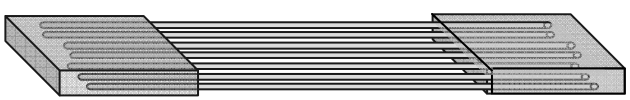


Image from [*]



Pd contacts provide reliable, highly reproducible, and low-resistance (~600Ω<<R_Q) connections to monolayer SWNT interconnects [*].

Many reports of more than 15μA in each SWNT with such contacts (4×10^8A/cm^2).

Current density in contacts can be much less than that in nanotubes.

Best candidates for taking advantage of the high current densities that SWNTs can potentially conduct.

[*] A. Javey, et al., *Physical Review Letters*, **92**, 106804 (2004).

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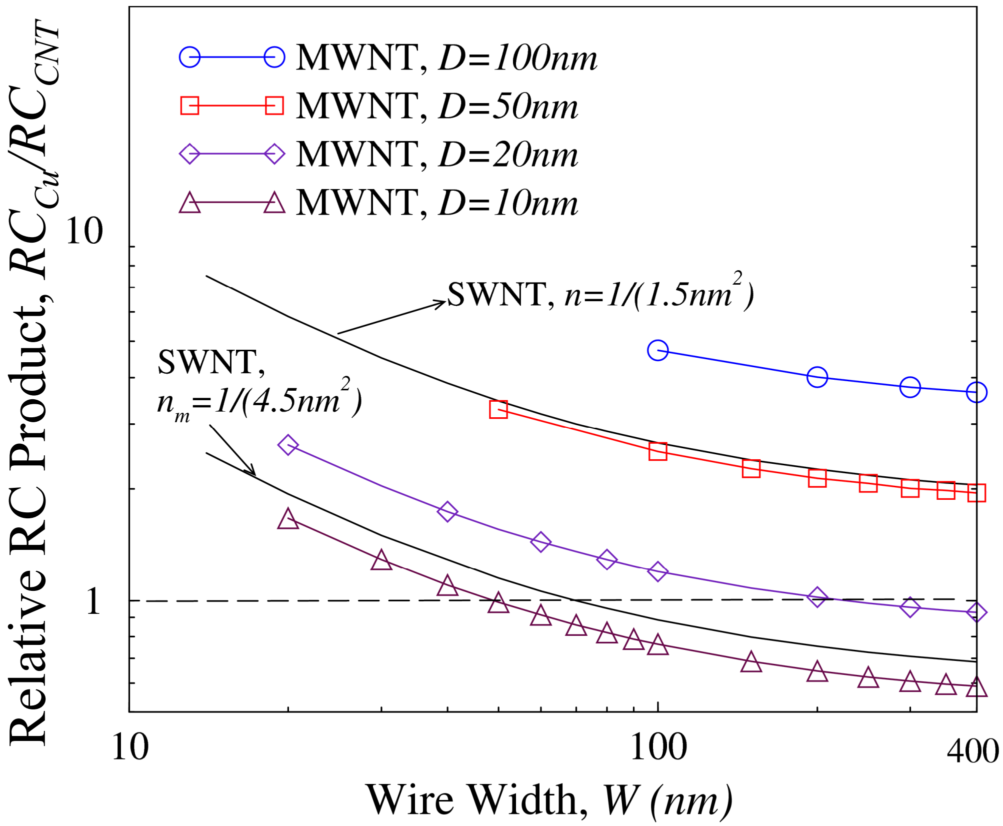
Semi-Global Signal Interconnects



Lower resistance and hence smaller RC delay

Without repeaters: $\tau \propto RC$

With repeaters: $\tau \propto \sqrt{RC}$

Large speed improvements for small wire dimensions by SWNTs

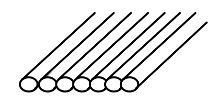
For a larger *W*, MWNTs with larger diameters offer higher speeds

A. Naeemi and J. Meindl, to be presented at *DAC*, June 2007.

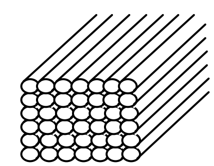
Conclusions

We need to look for novel ways to take advantage of the unique properties of carbon nanotubes.

Cross-sectional dimensions of nanotubes can be controlled by chemistry.



Short thin SWNT interconnects offer 50% reduction in average capacitance.



Bundles of densely packed SWNTs outperform copper wires in terms of resistance for W<50nm.

For long lengths large MWNTs can potentially offer conductivities several times larger than copper and SWNT-bundles.