Possible Implementation of Semiconducting Multiwalled Carbon Nanotubes as On-chip Interconnects

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Contents

Requirements for on-chip interconnects

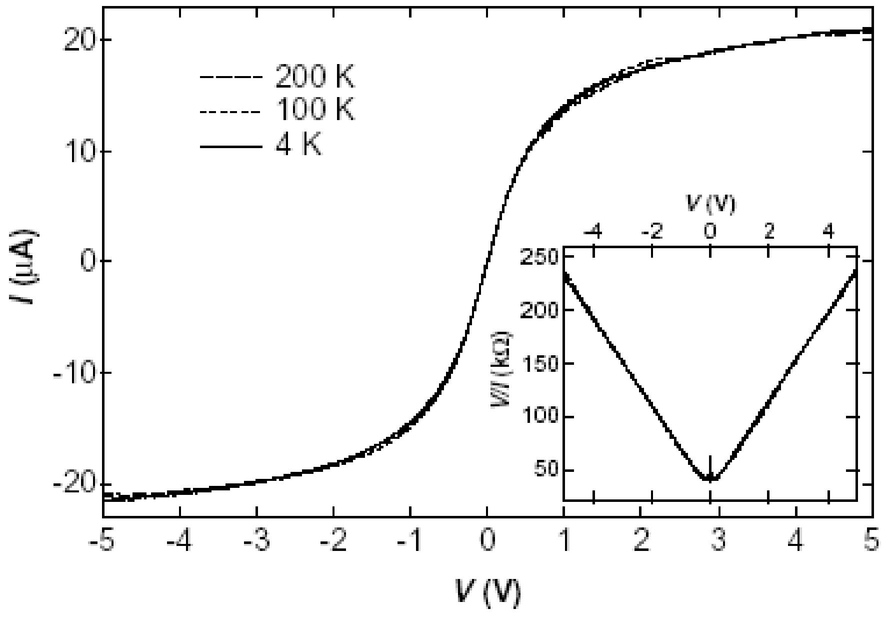
- Materials that can carry large current

  A high current-carrying capacity is critical for interconnect applications and reliability.

- Materials should have low resistance

- High thermal stability, etc.

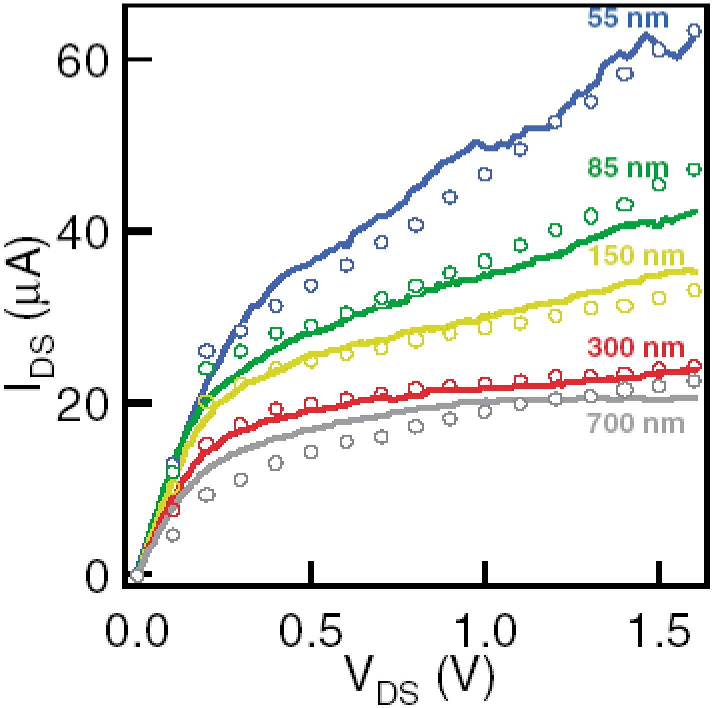
IV characteristics of SWNTs



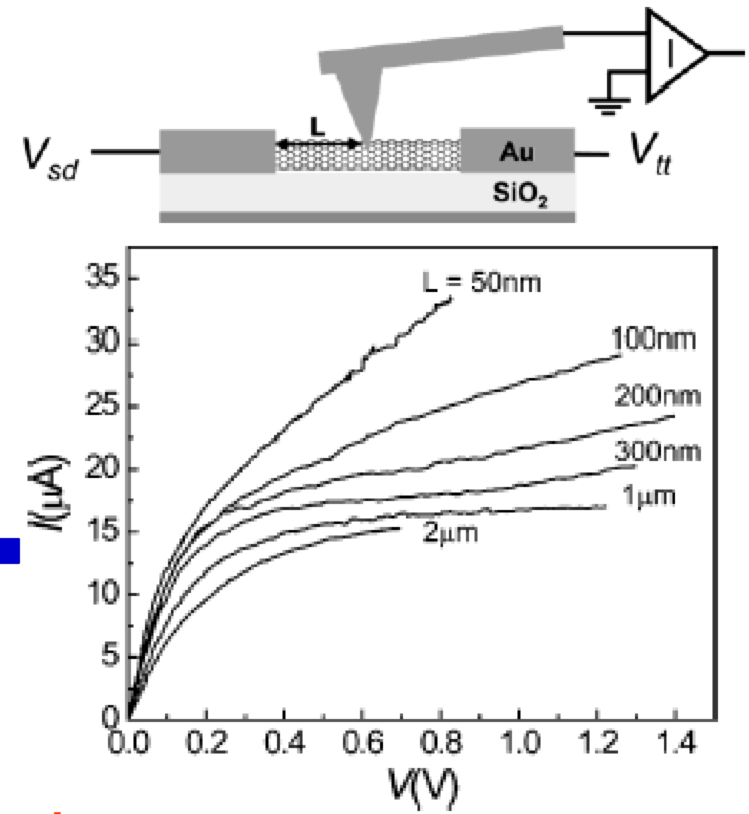
Current through NT is 10^9 A/cm^2

Z. Yao, C. L. Kane & C. Dekker, Phys. Rev. Lett. 84, 2941 (2000)

IV characteristics of SWNTs



A. Javey, J. Guo, M. Paulsson, Q. Wang, D. Mann, M. Lundstrom & H. Dai, Phys. Rev. Lett. 92, 106804 (2004).



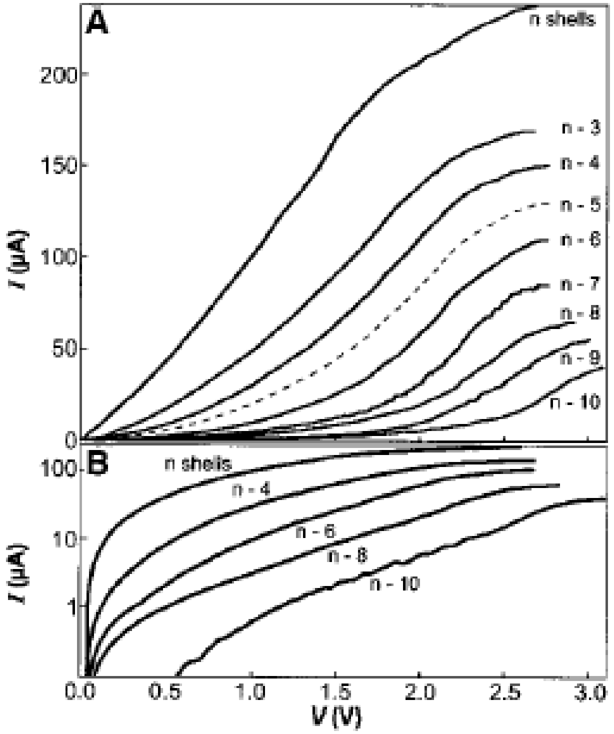
J.-Y. Park, S. Rosenblatt, Y. Yaish, V. Sazonova, H. Ustunel, S. Braig, T. A. Arias, P. W. Brouwer & P. L. McEuen, Nanoletters 4, 517 (2004).

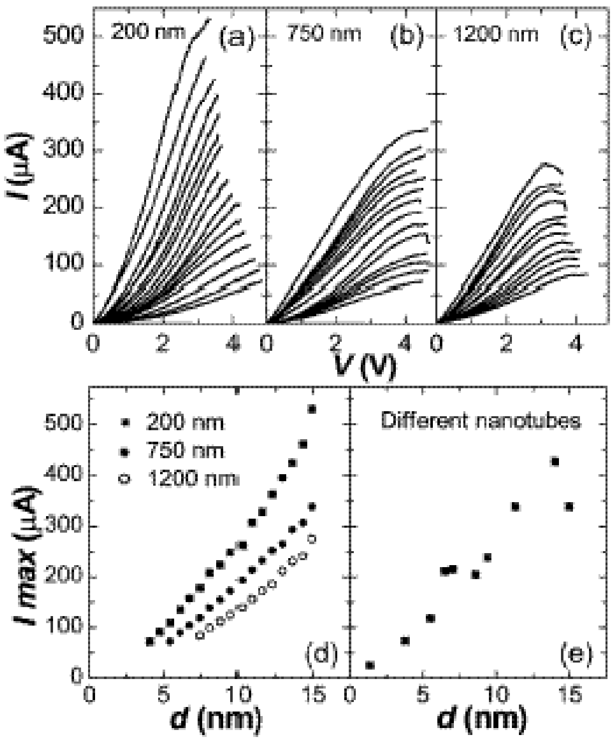
Current through a NT depends on length

IV characteristics of MWNTs

B. Bourlon, D.C. Glattli, B. Placais, J.M. Berroir, C. Miko, L. Forro & A. Bachtold, PRL 92, 026804 (2004).

P. G. Collins, M. S. Arnold and Ph. Avouris, Science 292, 706 (2001)

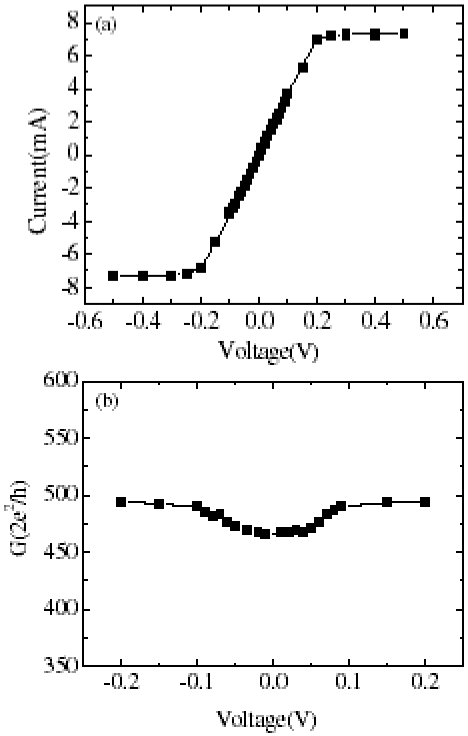




Current through NT depends on length and diameter of MWNTs

The layers can be either semiconducting or metallic

Current through MWNTs



Phys. Rev. Lett. **95**, 086601 (2005)

Resistance is 34.4 Ω

Current through MWNT is 7.27 mA

Corresponds to a current density of 10^8 A/cm^2

MWNT: d_{outer}=100 nm, d_{inner}=50 nm, length=6-30 mm

High conductance MWNT could prove to be viable as conductive wires in place of the copper or aluminum wires used in today's integrated circuits.

About transport properties NTs

Remarkable is the high current carrying capability of SWNTs as compared to superconductors

Current through NTs depends on length as well as diameter

MWNTs, in general, can carry larger current that increases with increasing diameter.

About transport properties NTs

- Resistance is few kΩ/μm.
  (Array is proposed for on-chip interconnects)
- Synthesis of semiconducting NTs has been reported.
  (Intertube distance may monitor the ultimate conductivity)
- Metallic ones burn away at a lower breakdown voltage.
- As metallic NT arrays has not been synthesized, one has to explore the possibility of semiconducting NT arrays or semiconducting MWNT.

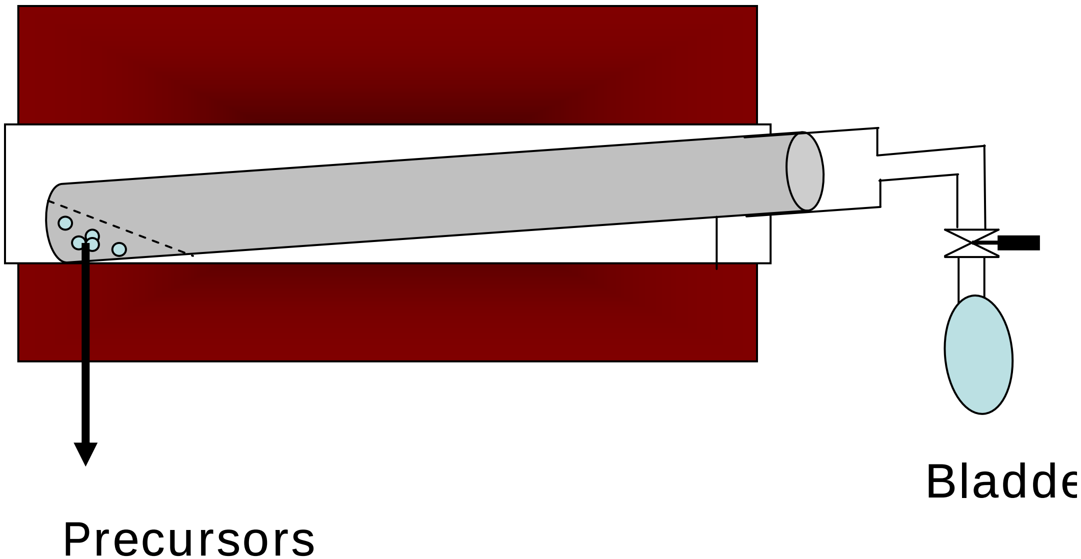
Our investigations

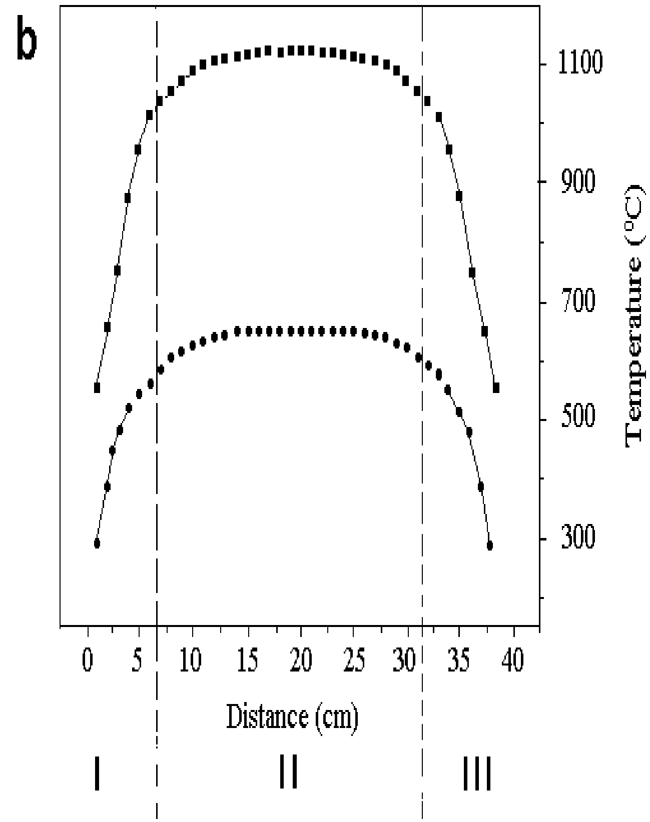
- Synthesis of NTs

- Transport properties of NT arrays
  (Current carrying capability, breakdown voltage etc.)

- Can these NTs be used for on-chip interconnect applications

Synthesis of aligned carbon nanotubes

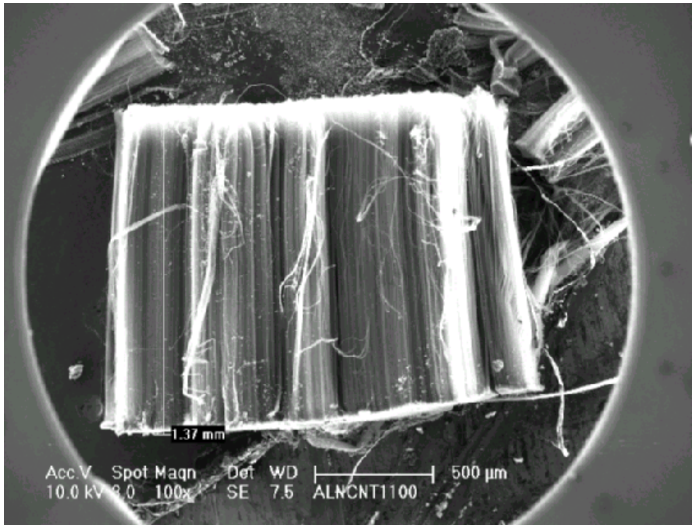


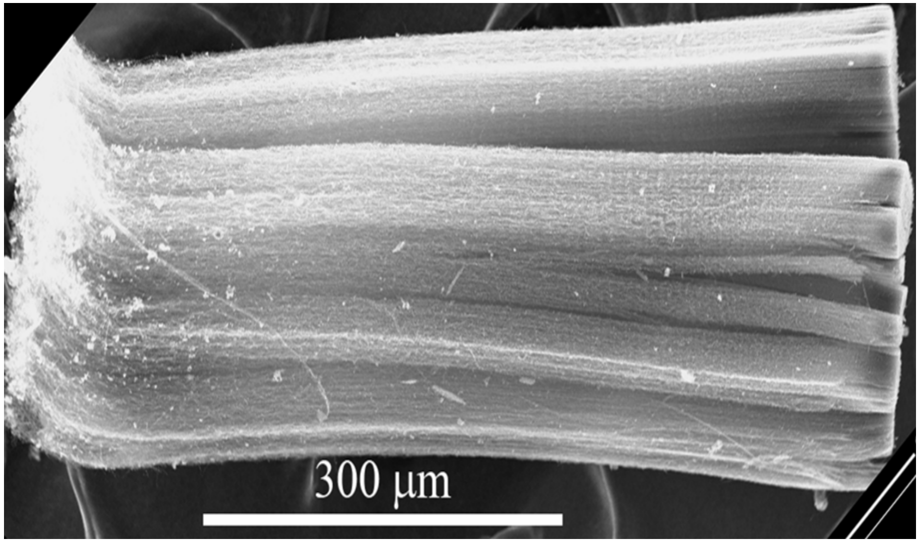


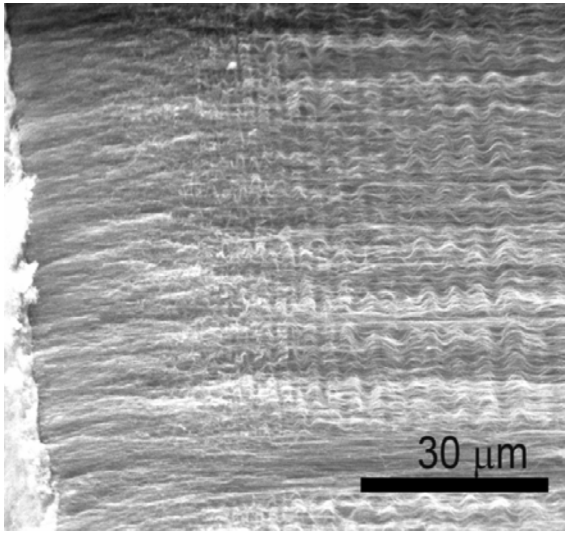
Catalyst precursor:Ferrocene

Carbon precursors: Benzene, THF, Benzene+THF

Experimental set up for aligned CNTs

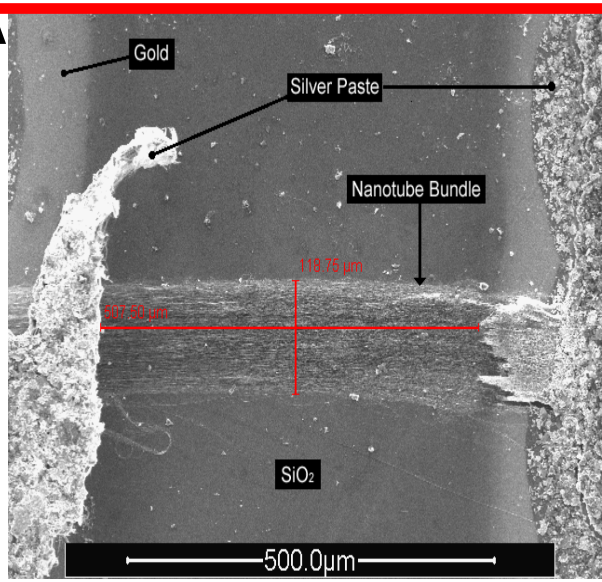




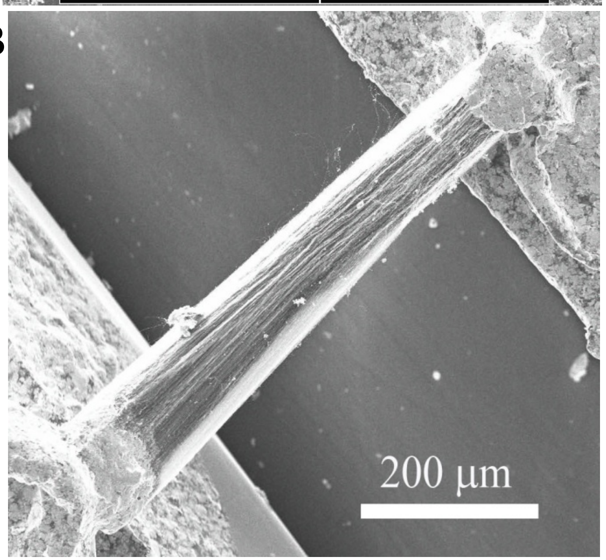


Fabrication of devices: characterization

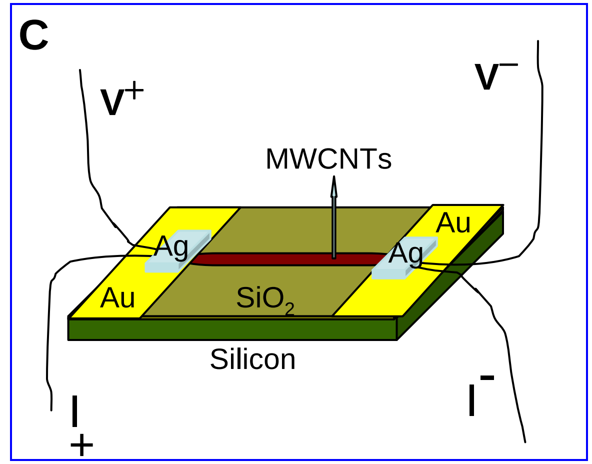
A

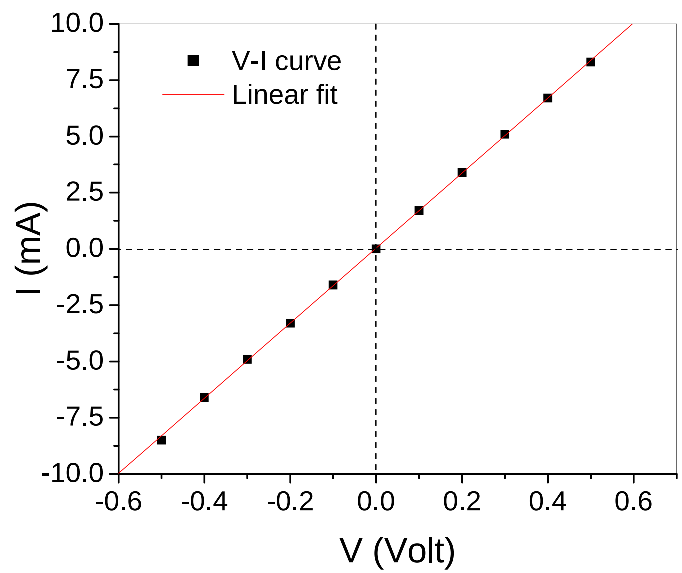


B



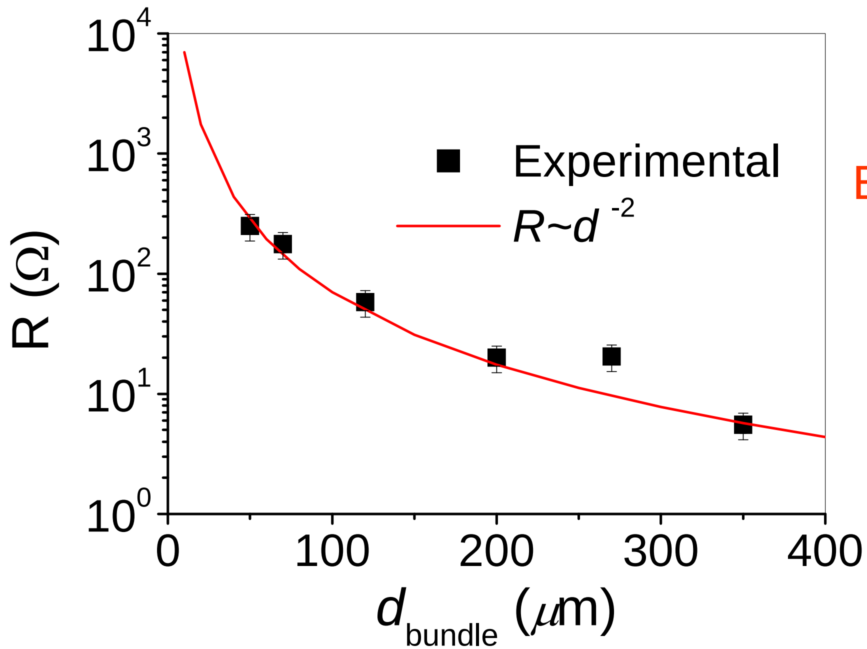
C





IV curve is linear at lower bias

Electrical characterisation: Results



Extrapolated R for a single NT is 250 kΩ/μm

L. Langer, J. Mater. Res. 9, 827 (1994): 2 μm long, 50 nm bundle, R_{10K}~450 kΩ

Y. Bando and co-wokers, Small 1, 1088 (2005): R is kΩ/μm

$R_{bundle}=R_{single}/N$

$N\sim2.5\times10^6$

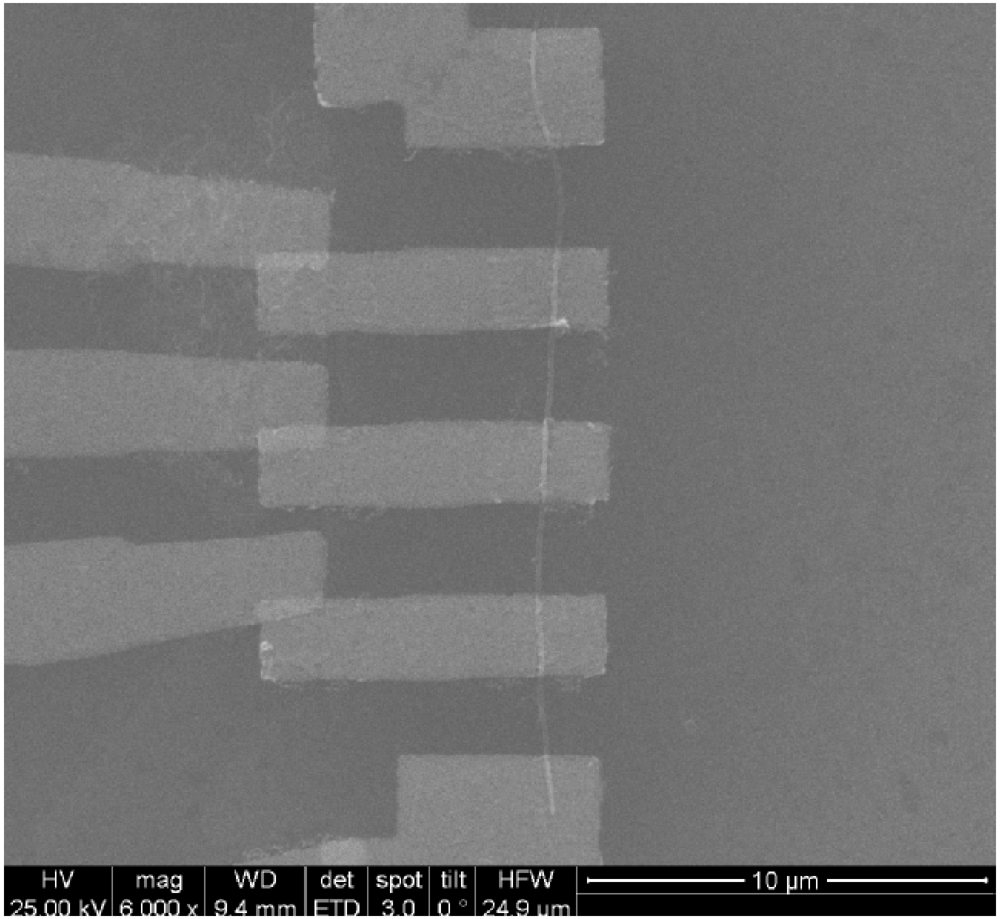
$R_{single}\sim M\Omega$

$R_{bundle}\sim\Omega$

Larger bundle diameter-
Lower resistance

P. Mahanandia & K. K. Nanda, Appl. Phys. Lett. **93**, 063105 (2008)

Investigation on individual NTs

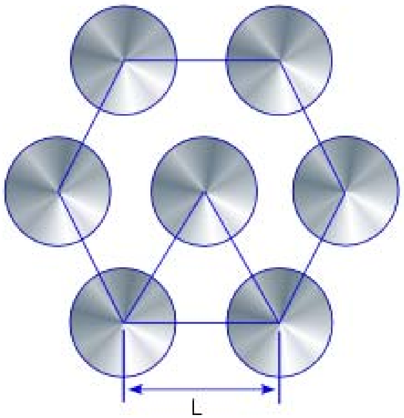


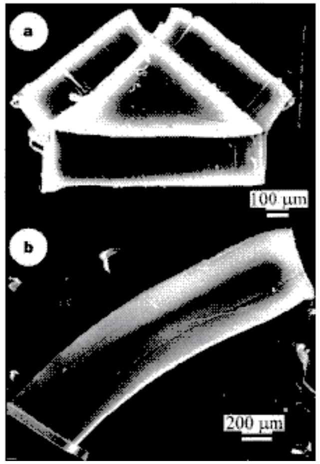
Resistance is ~4 kΩ/µm and the current through the NT is ~0.5 mA

Current through a SWNT is few μA while a MWNT can carry mA current

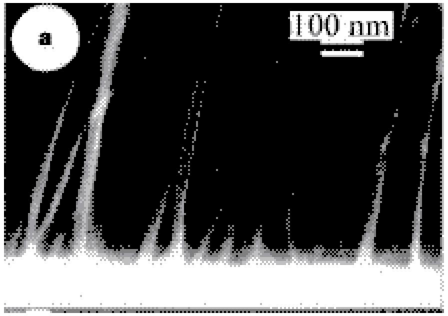
Few important issues of ropes

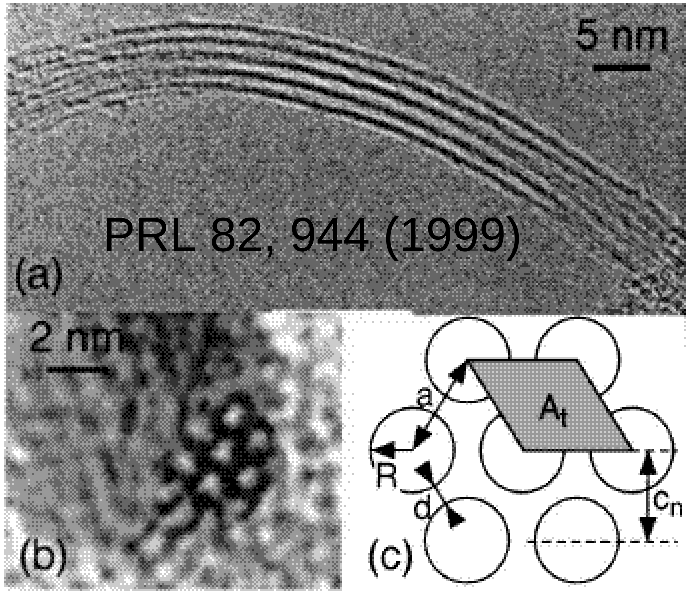
Intertube distance in a rope



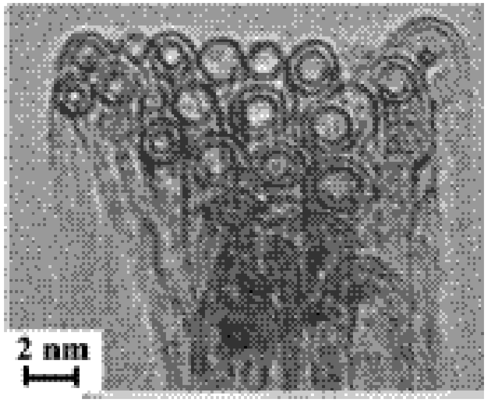


Nature **394**, 631 (1998).



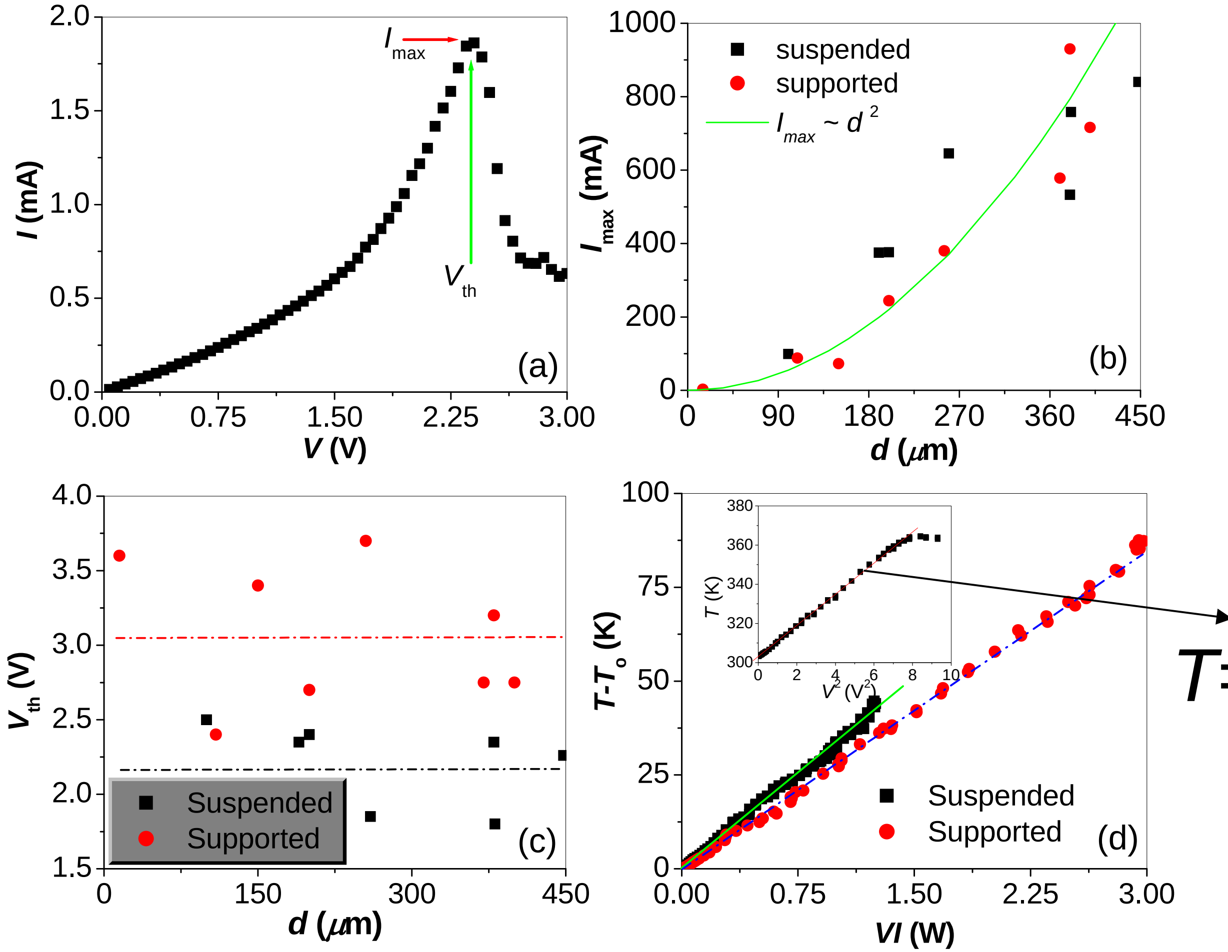


PRL 82, 944 (1999)



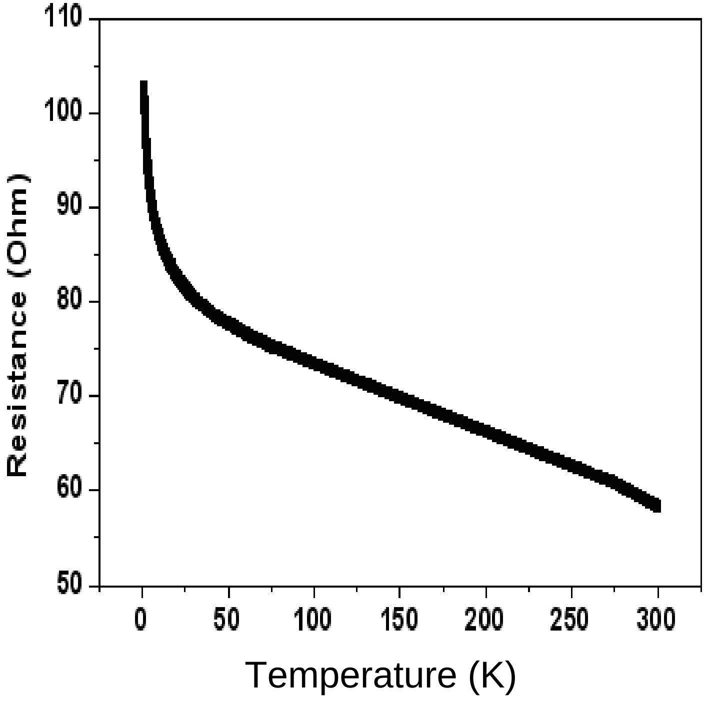
Chem Comm. 12, 1442 (2003).

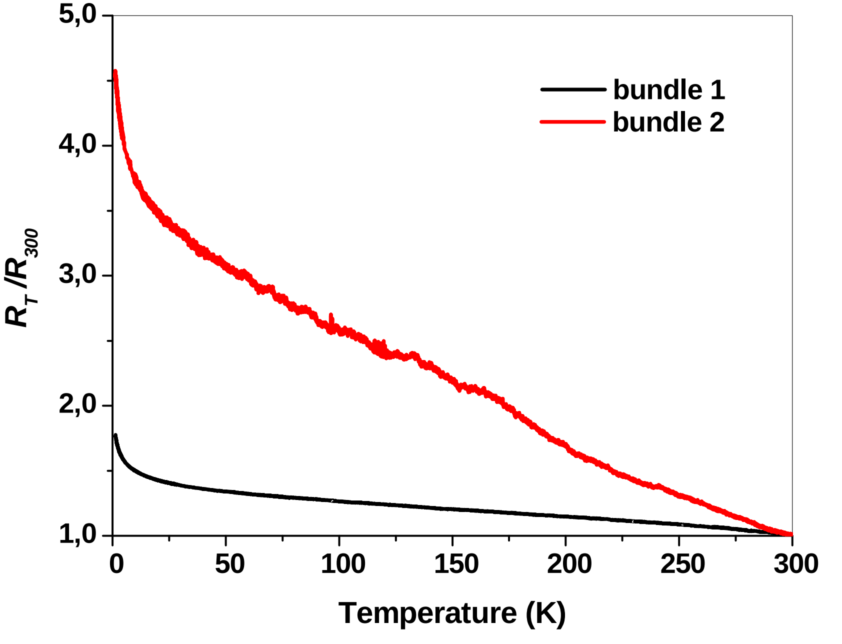
Electrical characterization: results



T=300+aV^2

Typical R-T curves

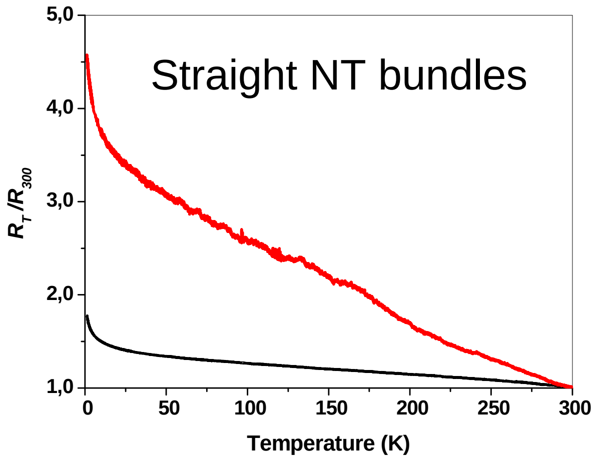




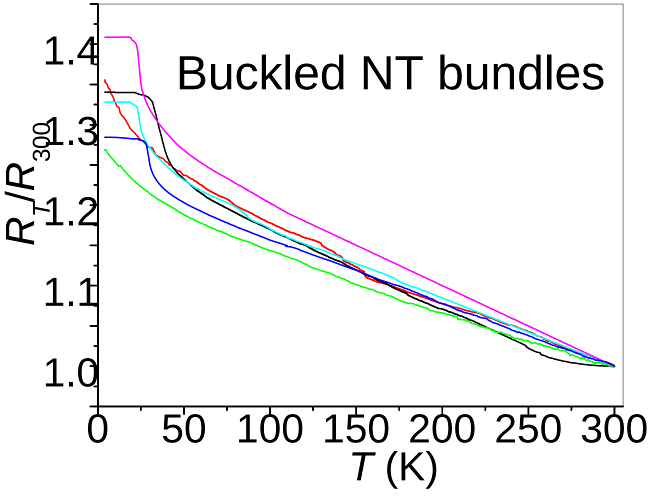
Variation is different for different bundles

P. Mahanandia, L. T. Singh & K. K. Nanda, Rev. Sci. Instrum. **79**, 053909 (2008)

Electrical characterization: Analysis



Mixture of metallic as well as semiconducting NTs !



Mostly semiconducting NTs !

Electrical characterization: analysis

Conductivity of a semiconductor is related to the temperature as

$$\frac{\sigma}{\sigma_0} = \exp\left(-\frac{E_g}{2kT}\right)$$

Current through the semiconductor is given by

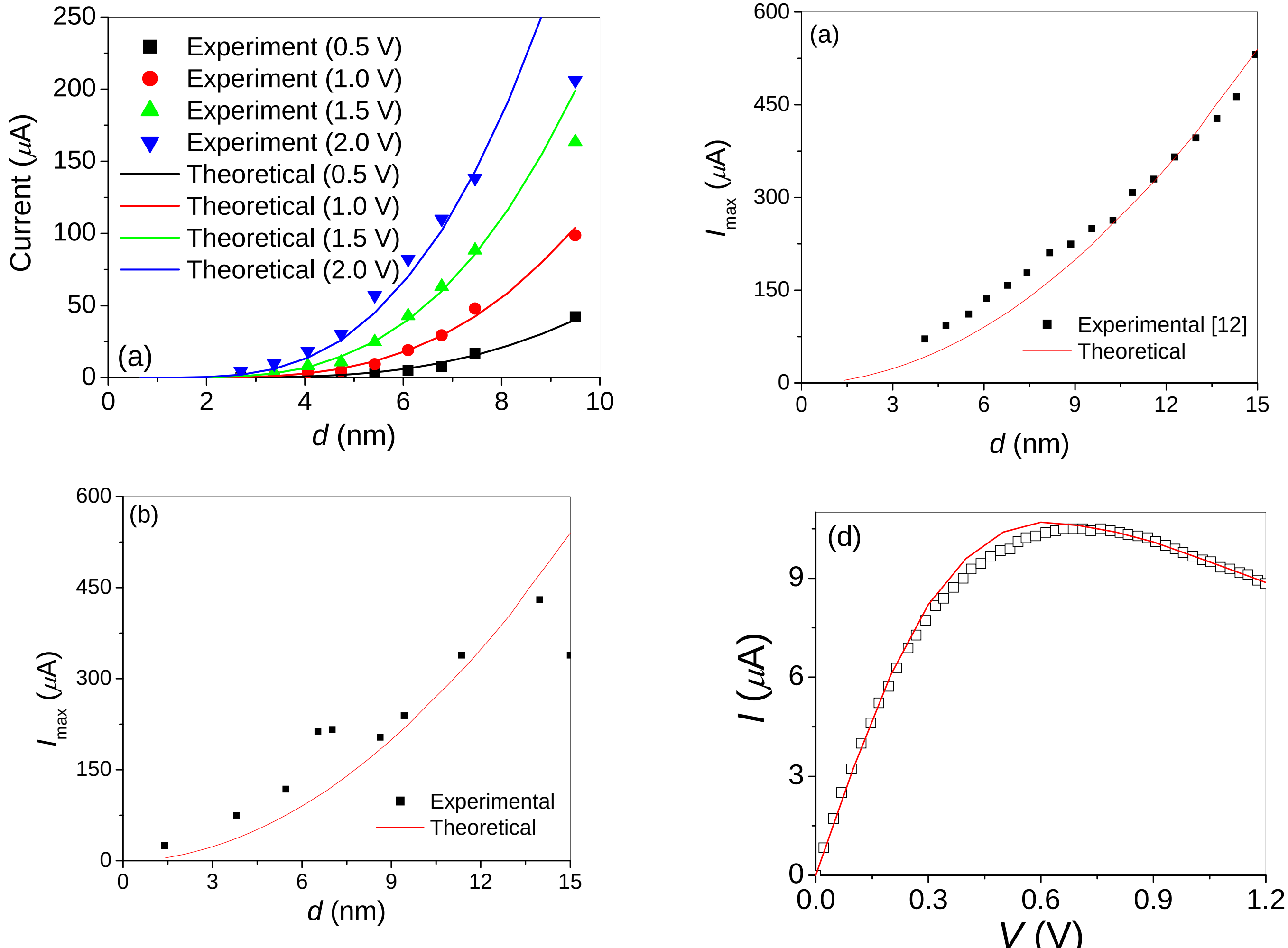
$$I = C_0 V d \exp\left(-\frac{E_g}{2kT(V)}\right)$$

can be applied to semiconducting NTs and to MWNTs. However, current through a MWNT is

$$I_{total} = \sum_{n=1}^{n_{tot}} I_n = C_0 V \sum_{n=1}^{n_{tot}} d_n \exp\left(-\frac{E_{gn}}{2kT}\right)$$

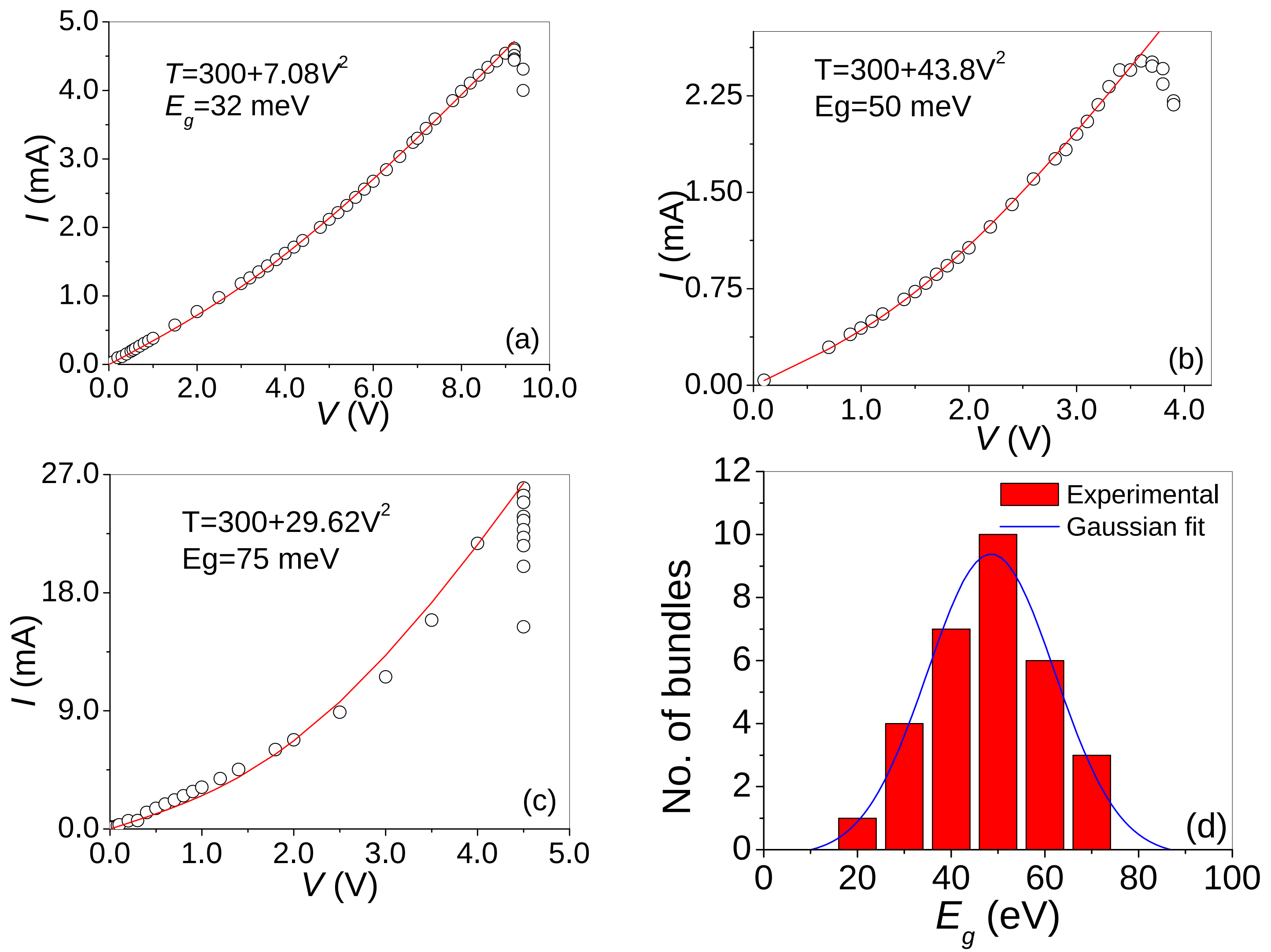
when all the shell participates.

Theoretical testing



Science **292**, 706 (2001), Phys. Rev. Lett. **92**, 026804 (2004), Phys. Rev. Lett. **95**, 155505 (2005).

Electrical characterization: analysis



E_g=20-70 meV

Electrical characterization: analysis

Conductivity of a semiconductor is related to the temperature as

$$\frac{\sigma}{\sigma_0} = \exp\left(-\frac{E_g}{2kT}\right)$$

Current through the semiconductor is given by

$$I = C_0 V d \exp\left(-\frac{E_g}{2kT(V)}\right)$$

can be applied to semiconducting NTs and to a shell of multiwalled NTs. However, current through a MWNT is

$$I_{total} = \sum_{n=1}^{n_{tot}} I_n = C_0 V \sum_{n=1}^{n_{tot}} d_n \exp\left(-\frac{E_{gn}}{2kT}\right)$$

when all the shell participates.

MWNT versus SWNT rope

$$R_{rope} = R_{individual} / n_{tot}$$

$$I_{\max,rope} = n_{tot} I_{\max,individual}$$

$$\frac{1}{R_{MWNT}} = \sum_{n=1}^{n_{tot}} \frac{1}{R_n}$$

$$I_{MWNT} = \sum_{n} I_n$$

Current through a semiconducting and metallic MWNT is at least *three to four* times higher than that of a metallic SWNT rope with the same diameter.

Overall, the current through a MWNT is expected to be 10^3 times higher than that of a SWNT

Summary

Resistance of the arrays increases with array diameter

Current capability increases

Threshold voltage is almost independent

Temperature coefficient is negative for resistance

Semiconducting arrays/MWNTs can be suitable as on-chip interconnects

Few challenges

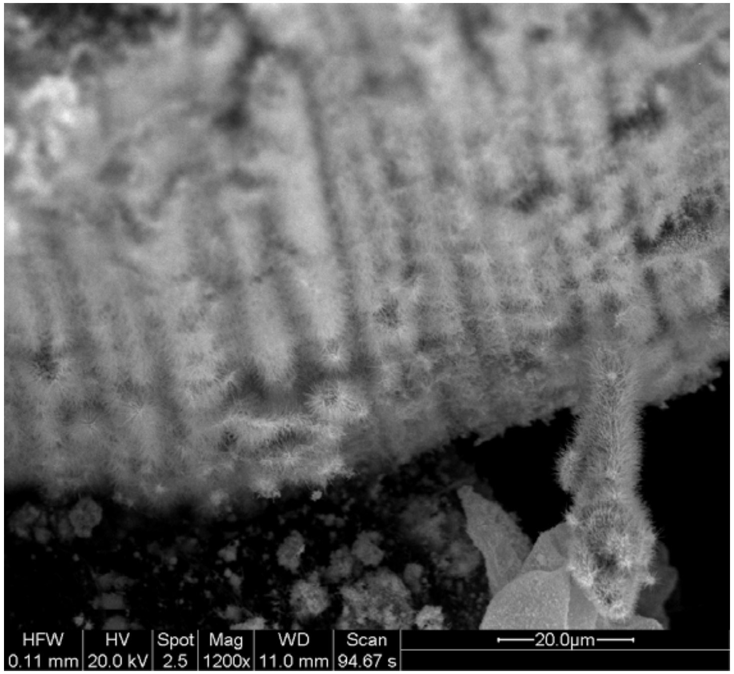
To achieving ultimate conductivity

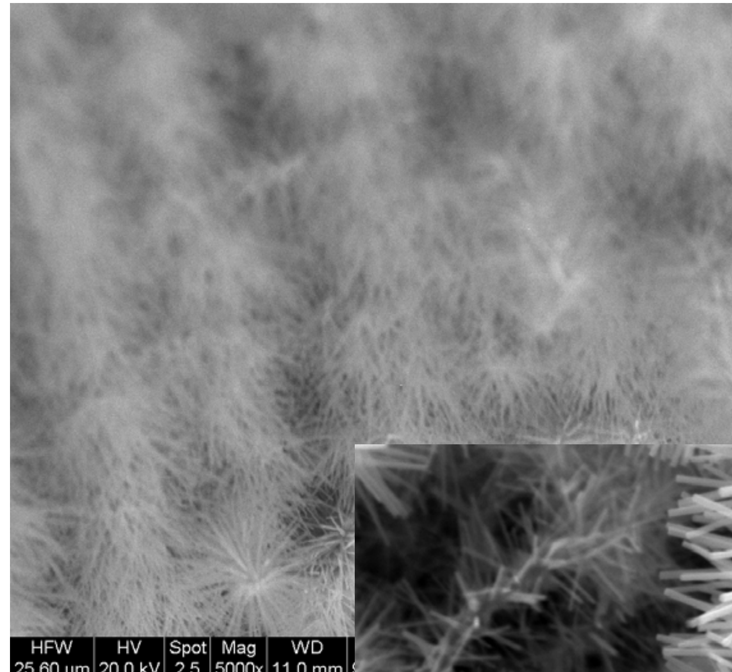
A rope with only metallic nanotubes

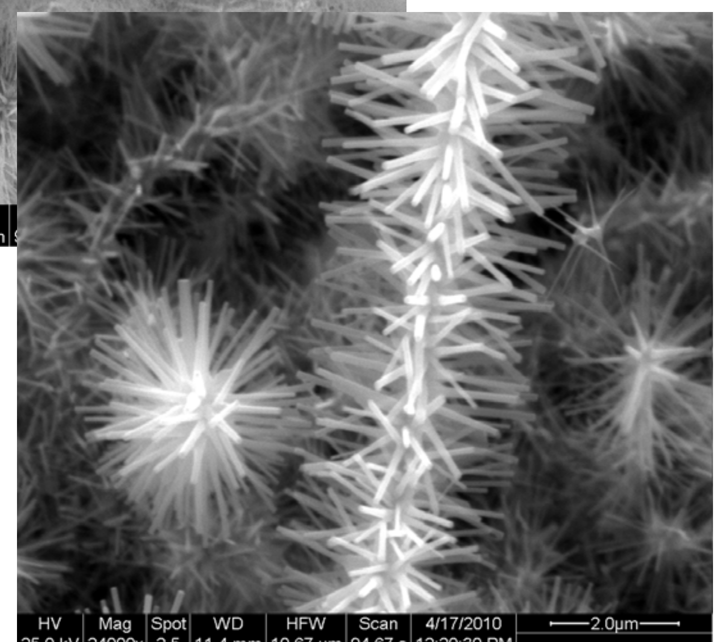
MWNTs with more number of layers

Increased threshold voltage

Site specific growth ZnO Nanostructures on CNT – on Side Wall

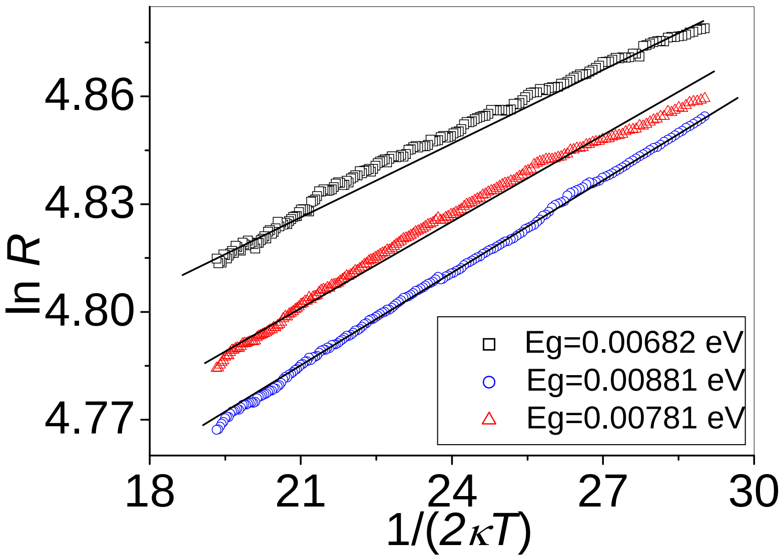






THANKING YOU

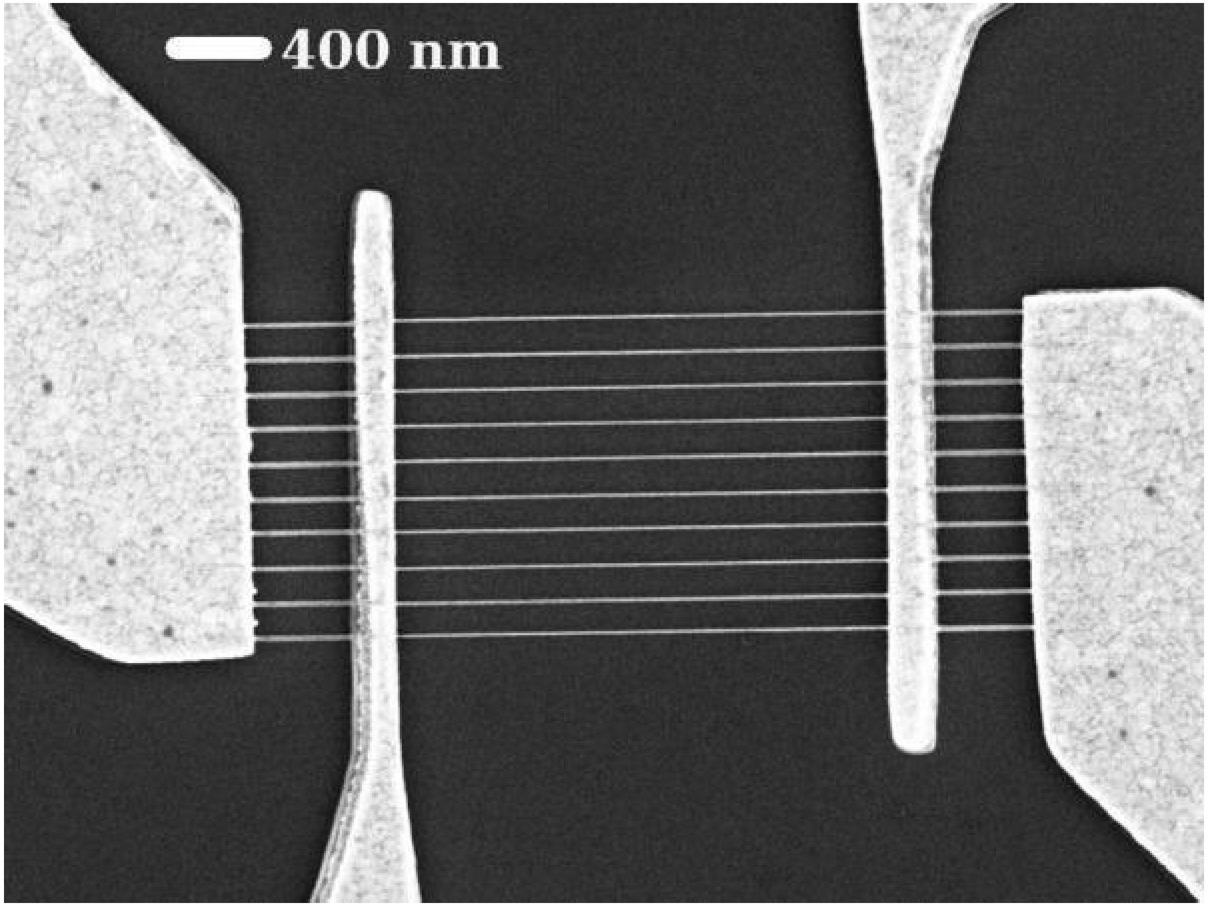
Temperature coefficiencts



Theoretical band gap of a single-walled NT depend on the diameter as,

$$E_g = 2\gamma_0 a_{C-C} / d$$

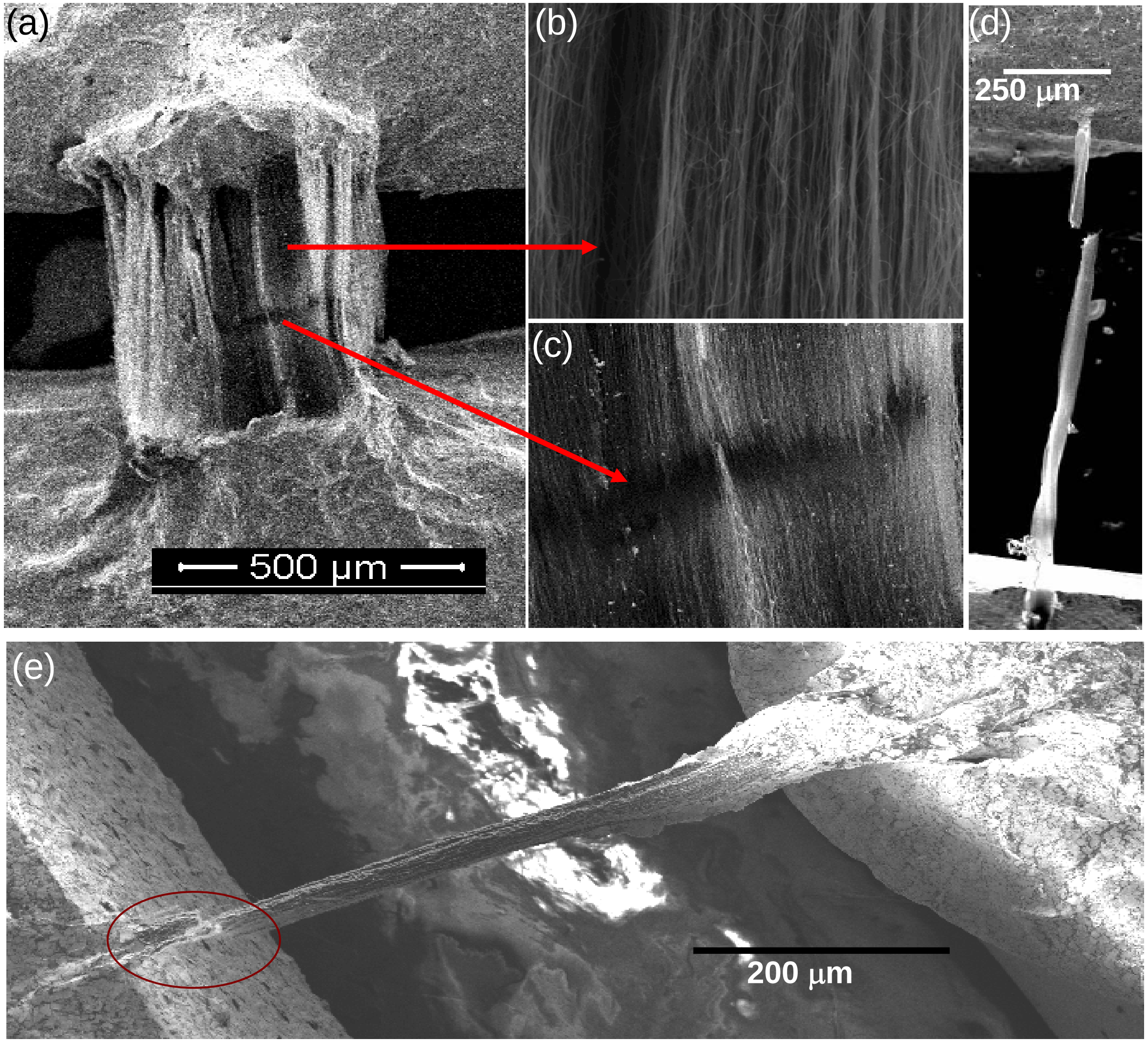
γ_0 is the C–C tight-binding overlap energy (~2.1-2.7 eV)
a_{C-C} the nearest neighbour C–C distance (0.142 nm)
and d the diameter.

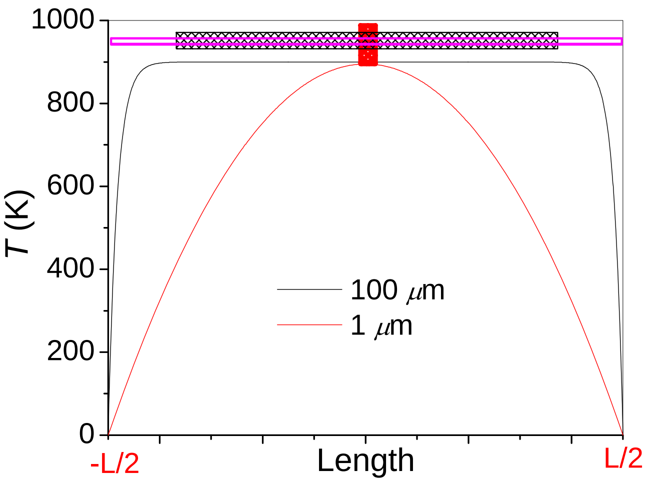

400 nm

A high current-carrying capacity is critical for interconnect applications and reliability.

IEEE Trans. Nanotechnol. **7**, 624 2008.

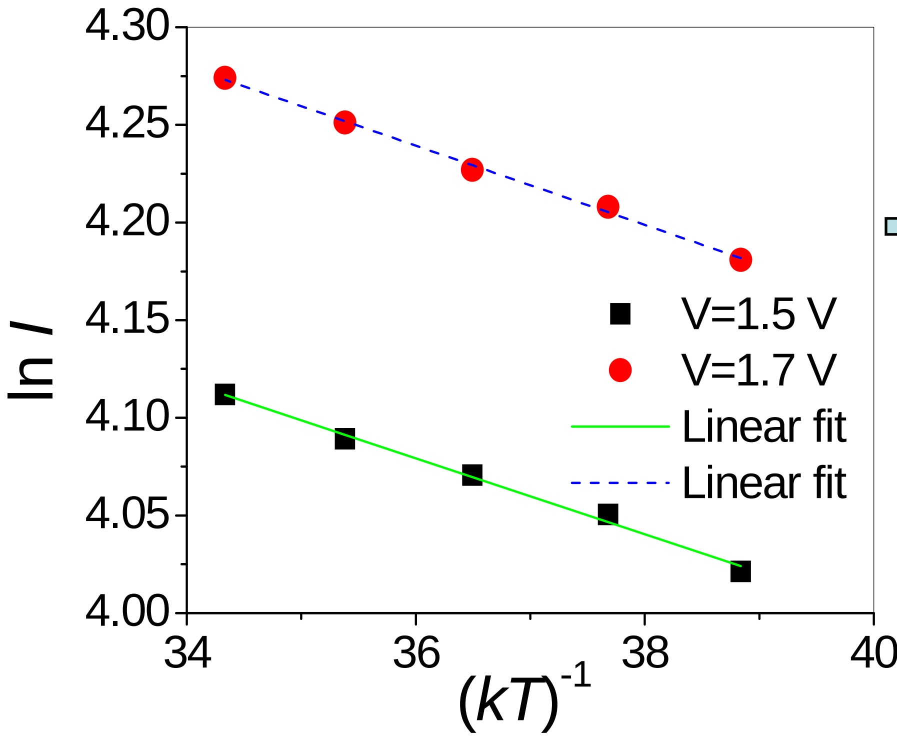
Breakdown of NT bundles





Breakdown does not necessarily occurs at the middle

Electrical characterization: analysis

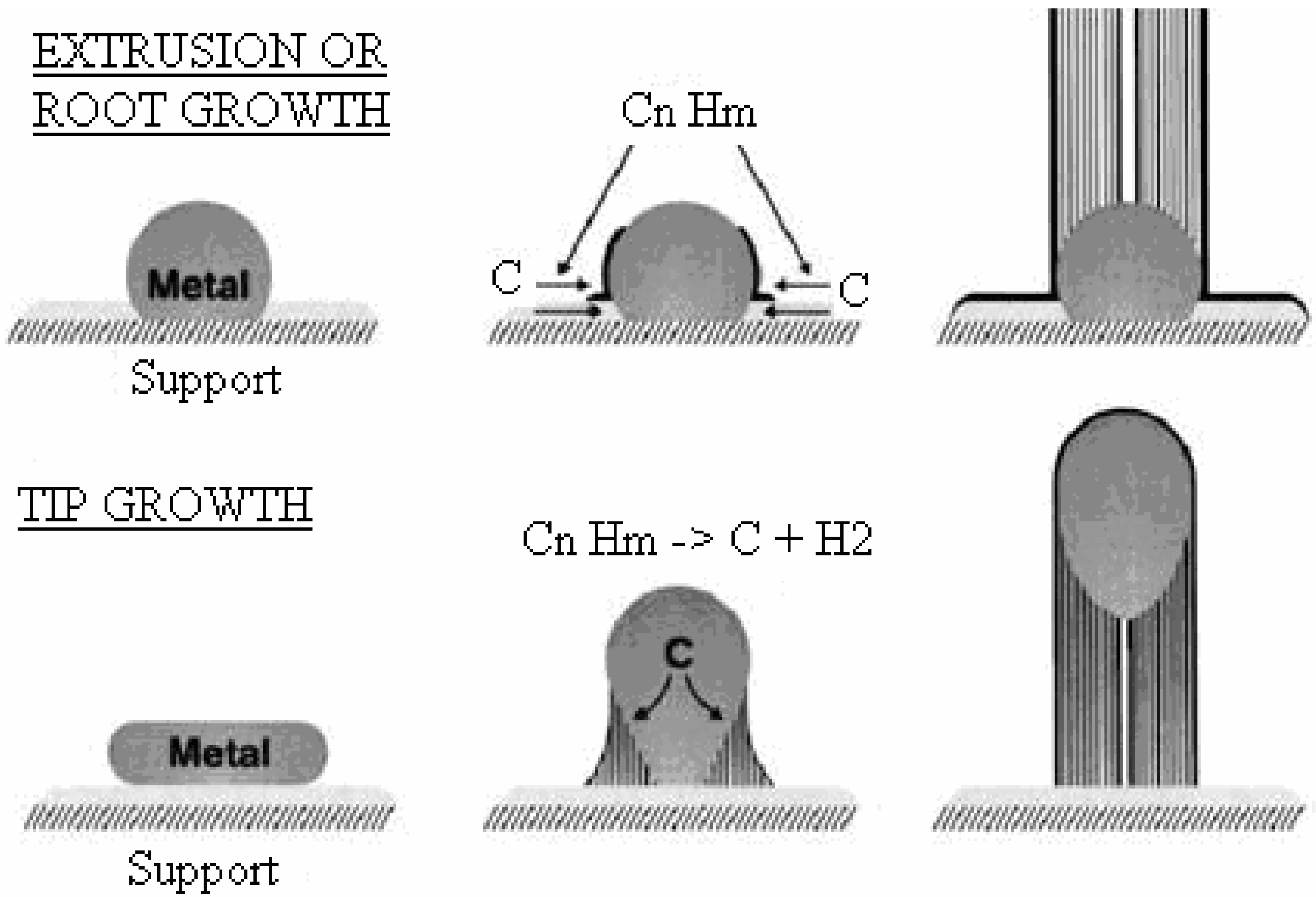


E_g=30-70 meV

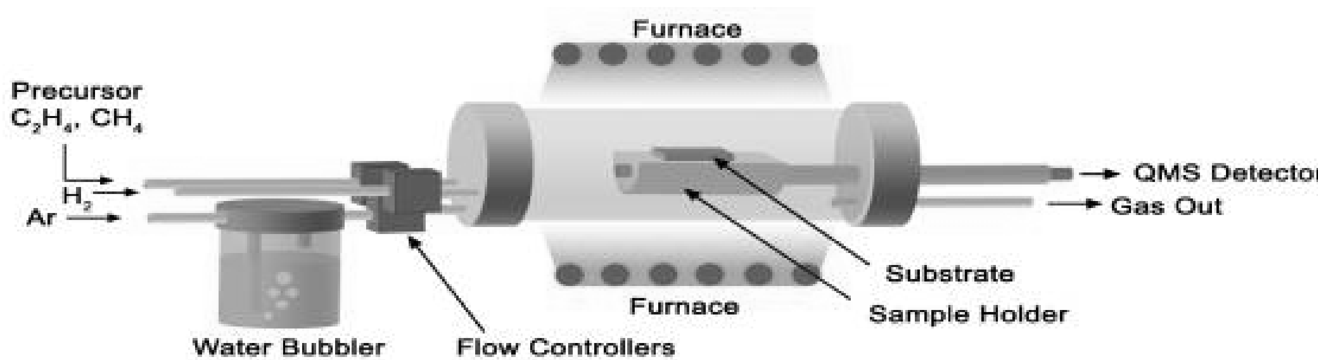
Theoretical band gap: $$E_g = \frac{\Gamma}{d}$$

Only outer shell conducts !
Outer diameter = 50 nm estimates a theoretical band gap of ~15 meV
Probably, inner shells also conduct !

Growth mechanisms



Schematic of CVD set up (tip/root growth)

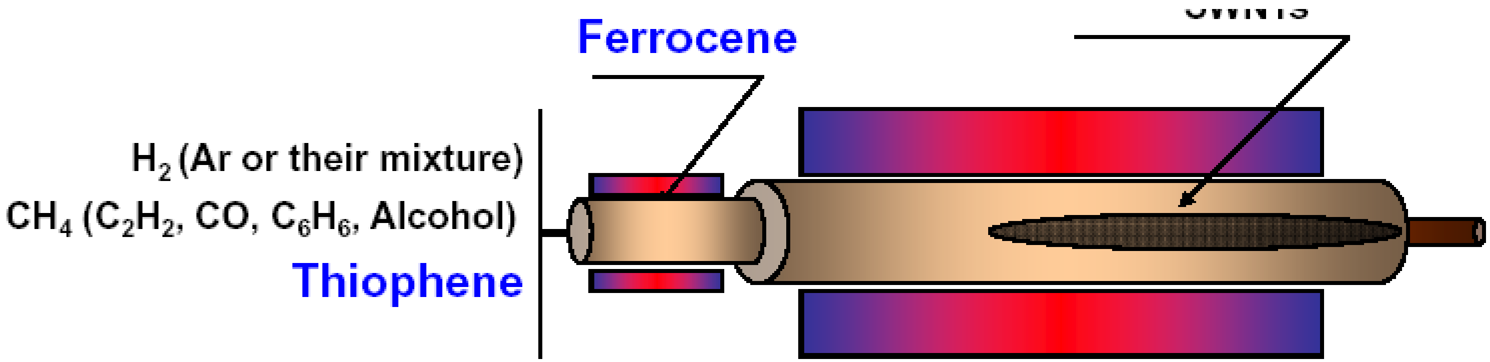


Predeposited catalysts

Strong interaction – root growth

Weak interaction – tip growth

Schematic of CVD set up (floating catalyst)



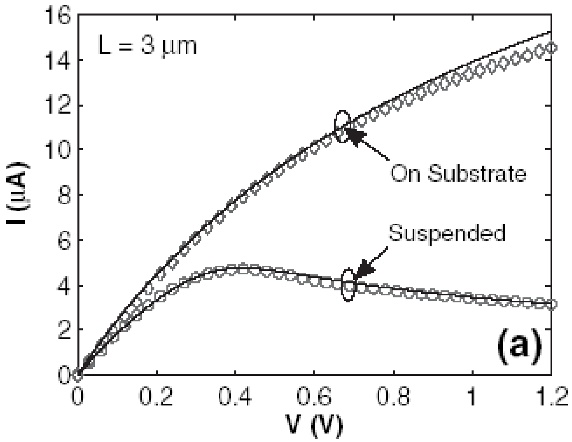
Deposition of catalyst is not required

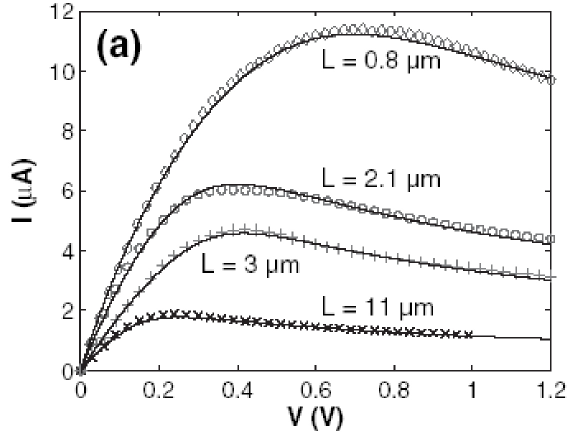
But requires two furnaces

Metal catalysts are introduced in a continuous way

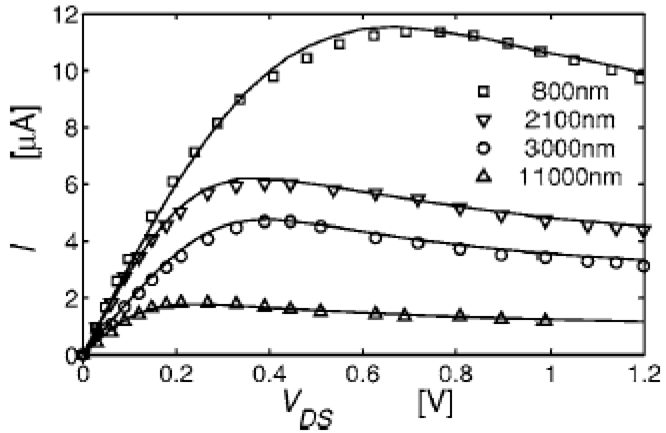
IV characteristics of SWNTs

E. Pop, D. Mann, J. Cao, Q. Wang, K. Goodson & H. Dai, PRL **95,** 155505 (2005),

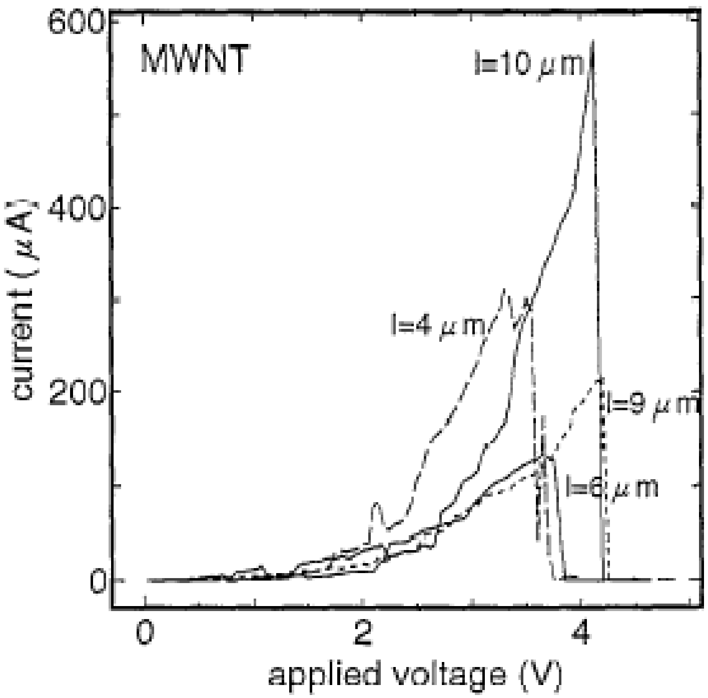




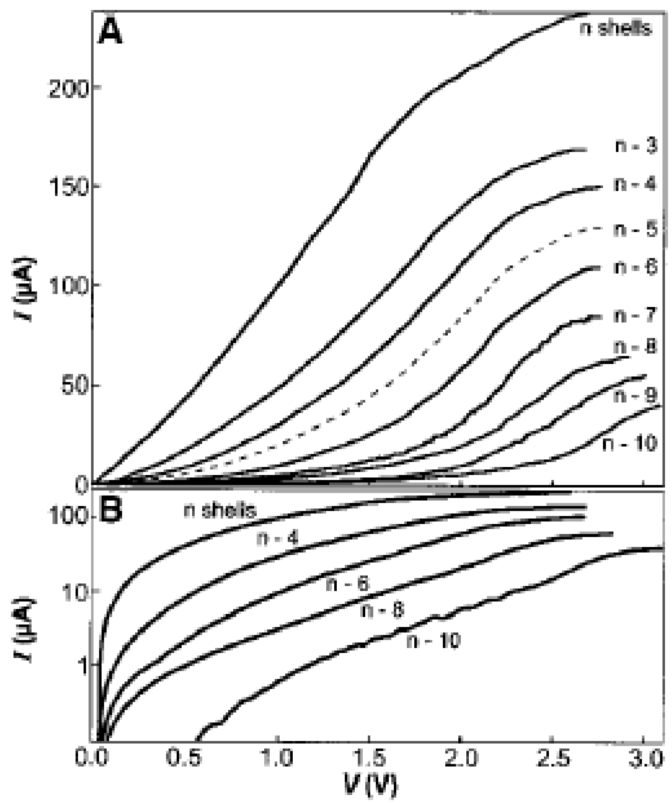
M. A. Kuroda and J.-P. Leburton, APL 89, 103102 (2006)



IV characteristics of MWNTs



K. Kaneto, M. Tsuruta, G. Sakai, W. Y. Cho and Y. Ando, Synt. Metals 103, 2543 (1999)



P. G. Collins, M. S. Arnold and Ph. Avouris, Science 292, 706 (2001)