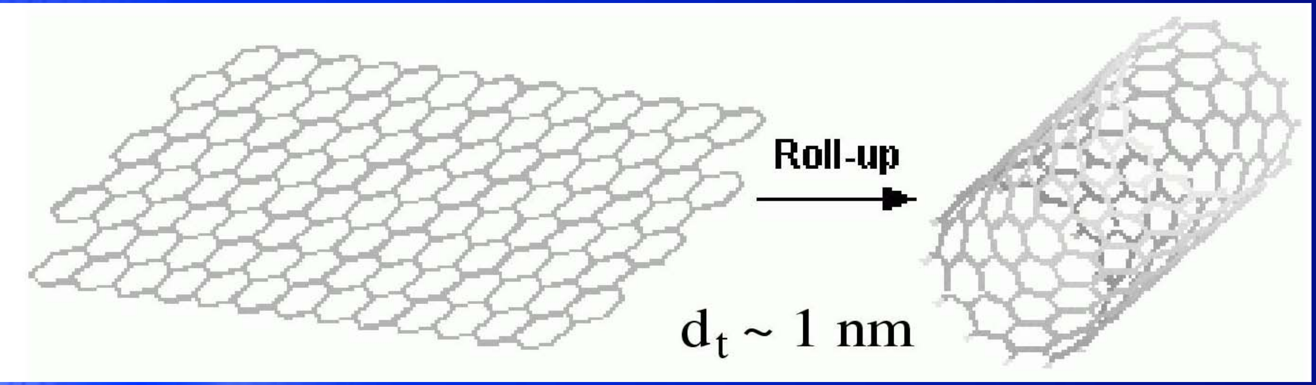
# Carbon Nanotubes for Nanoelectronics

***- Synthesis and Integration***

Yuegang Zhang
The Molecular Foundry, LBNL

10/24/2008

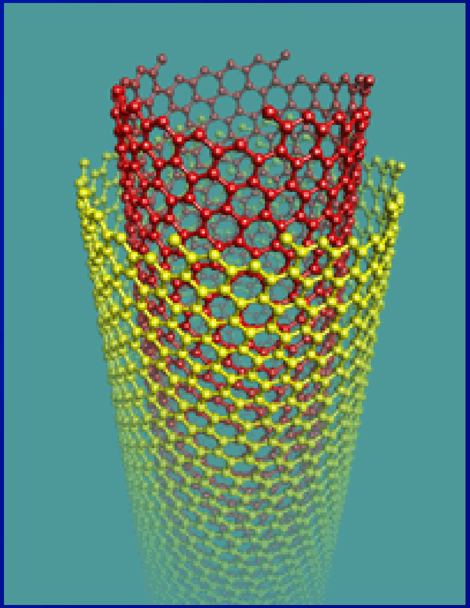
# What is Carbon Nanotube?




graphene sheet

SWNT

MWNT

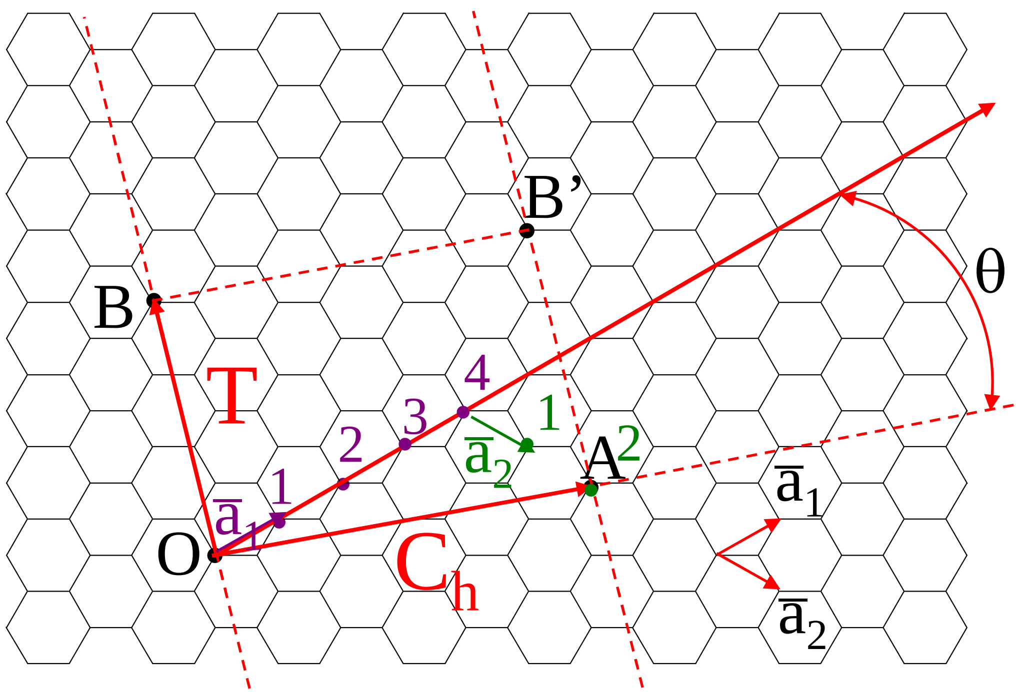


- ✓ Single-walled nanotube (SWNT) consists of a single layer of graphene sheet.
- ✓ Multi-walled nanotube (MWNT) consists of a set of concentrically nested SWNTs. The inter-shell distance is about 0.34 nm, similar to that of turbostratic graphite.

# Different Structures of Nanotubes

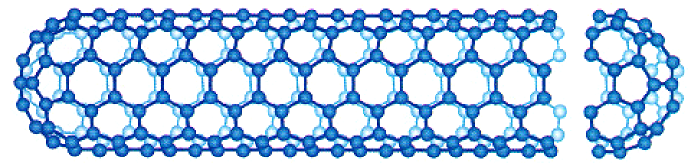
**Theoretically, there are indefinite ways to roll-up a graphene sheet into nanotubes. Each nanotube can be uniquely denoted by an index (*n*, *m*).**

$$\vec{C}_h = n\vec{a}_1 + m\vec{a}_2 \equiv (n, m) \Leftrightarrow \begin{cases} d_t = \dfrac{L}{\pi} = \dfrac{a}{\pi}\sqrt{n^2 + nm + m^2} \\ \theta = \tan^{-1}\dfrac{\sqrt{3}m}{2n+m} \end{cases}$$



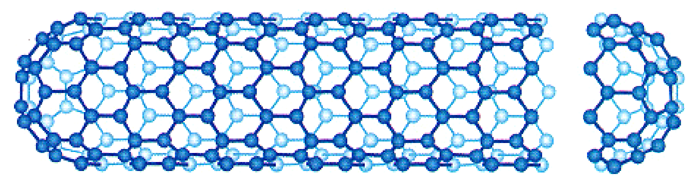

Example (4,2)

**armchair** $\theta = 30°$



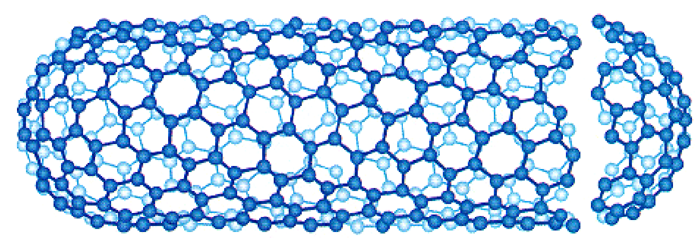
(n,m) = (5,5)

**zigzag** $\theta = 0°$



(n,m) = (9,0)

**chiral** $0 < \theta < 30°$



(n,m) = (10,5)



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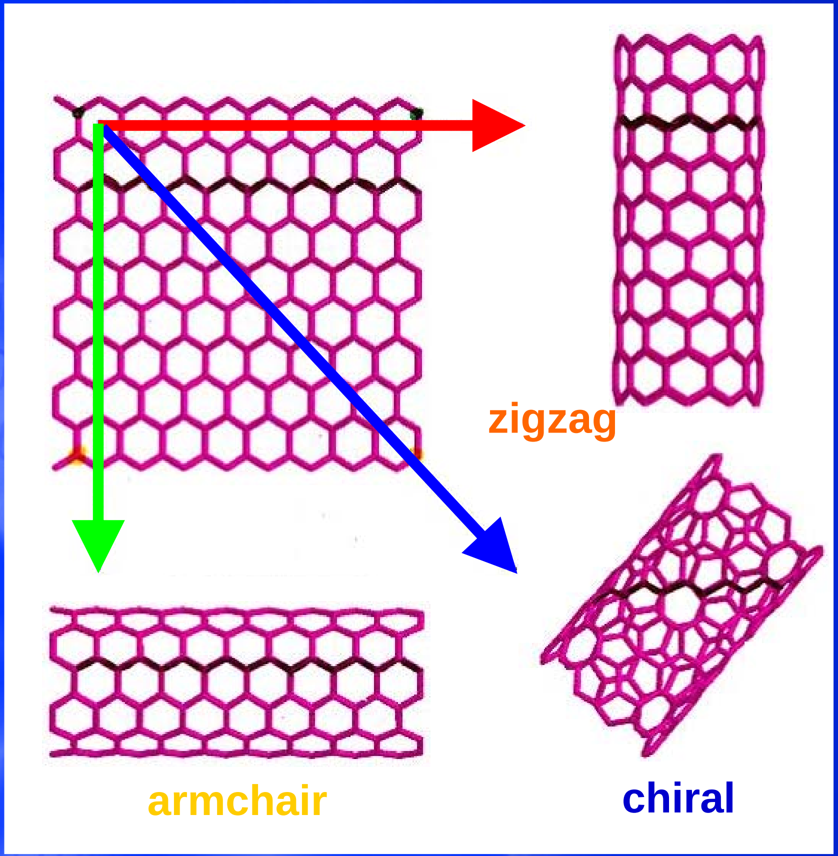
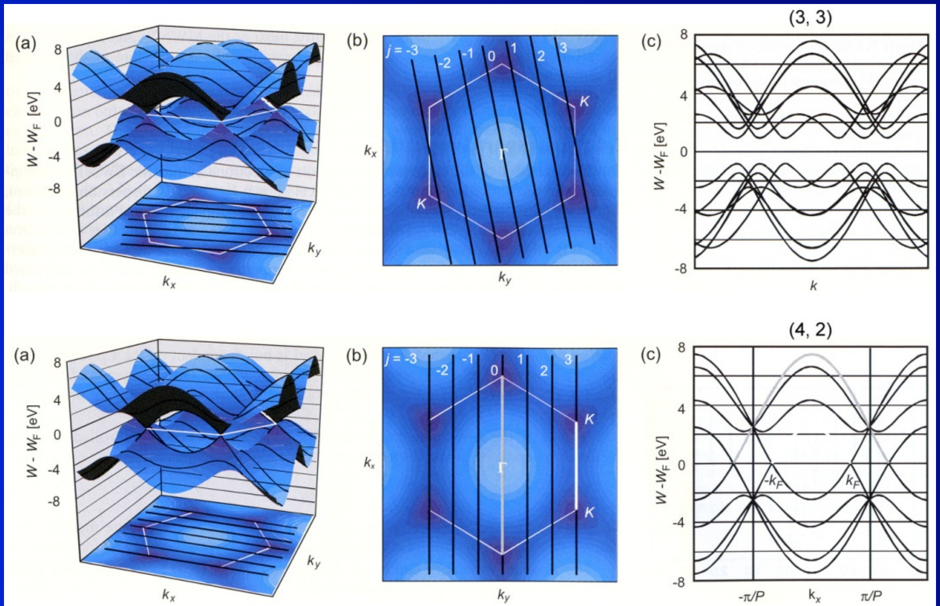
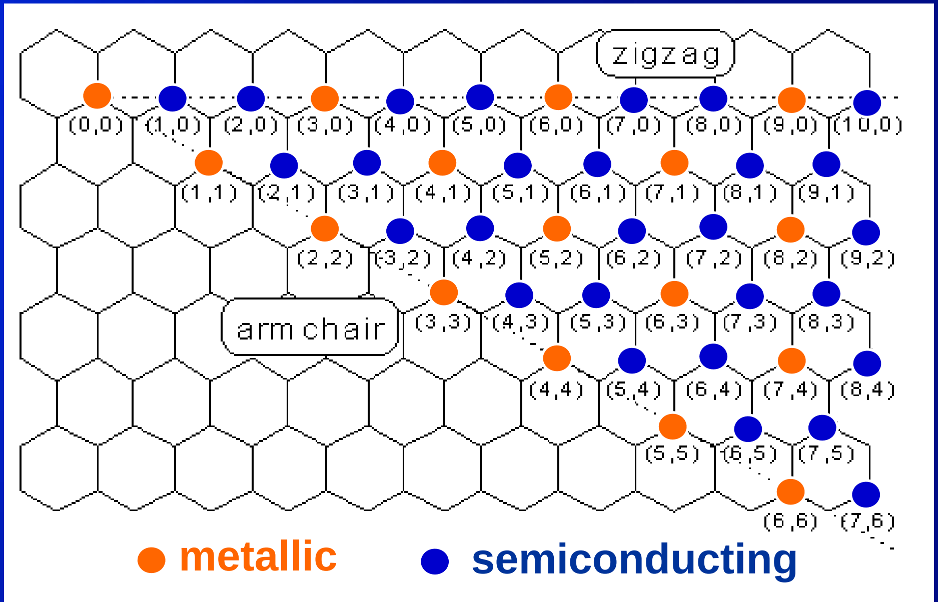
# Nanotube: Metal or Semiconductor?

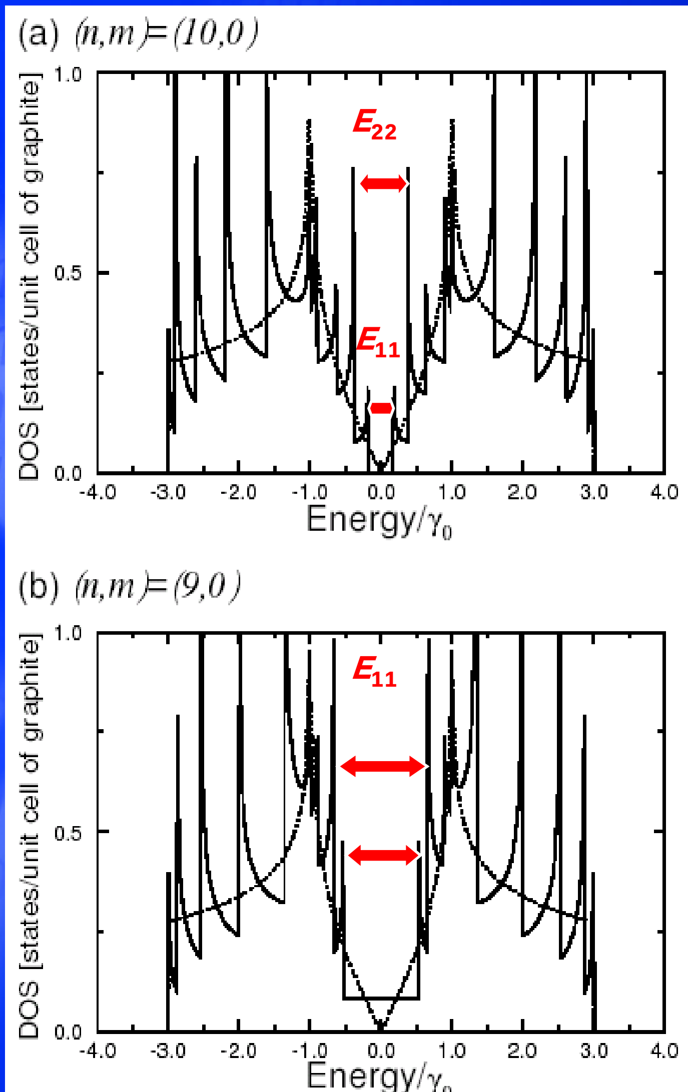


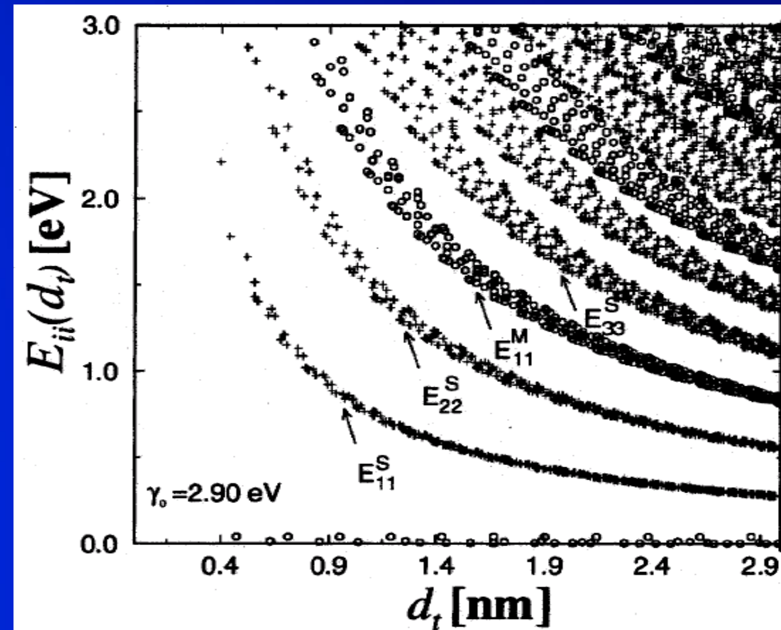

$$n - m = \begin{cases} 3p & \text{metal} \\ 3p \pm 1 & \text{semiconductor} \end{cases}$$



# Nanotube Structure vs Electronic Property




**The interband transition energies $E_{ii}$ are uniquely determined by the diameter and chiral angle**

**Diameter dependence:** $E_{ii} \propto 1/d_t$

e.g. Metallic tubes: $E_{11}^M \cong 6\ \gamma_0\ a_{C\text{-}C}\ /\ d_t$

Semicon. tubes: $E_{11}^S \cong 2\ \gamma_0\ a_{C\text{-}C}\ /\ d_t$

$E_{22}^S \cong 4\ \gamma_0\ a_{C\text{-}C}\ /\ d_t$

$E_{33}^S \cong 8\ \gamma_0\ a_{C\text{-}C}\ /\ d_t$

**Chiral angle θ dependence:**

The trigonal warping effects increases with decreasing chiral angle. This causes a deviation of $E_{ii}$ from $E_{ii} - d_t$ curves for chiral tubes (splitting or shifting of van Hove singularities).

# Why Nanotubes?

## *Perfect* geometry

- ~ 1 nm diameter
- 1-D nanowire with extremely high aspect ratio

## *Perfect* atomic structure

- Single crystal & single molecule

## *Perfect* properties

- Mechanical: resilience; tensile strength; Young's modulus
- Thermal: stability; conductivity
- Chemical: stability
- Electrical: metallic & semiconducting, ballistic transport, high current density, low electromigration rate, high carrier mobility…



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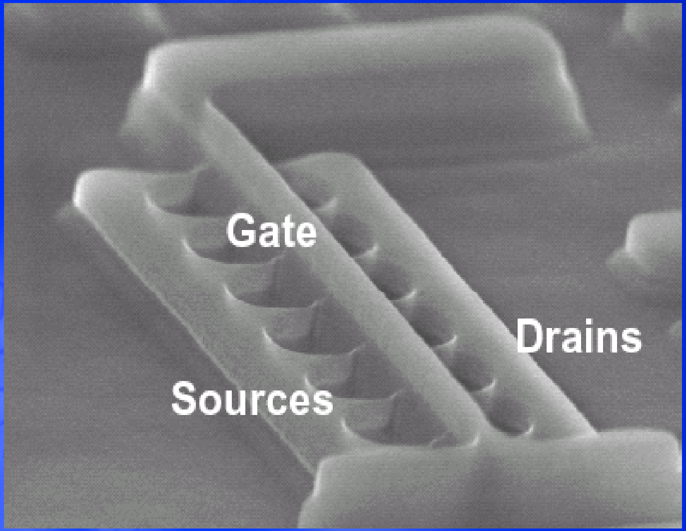
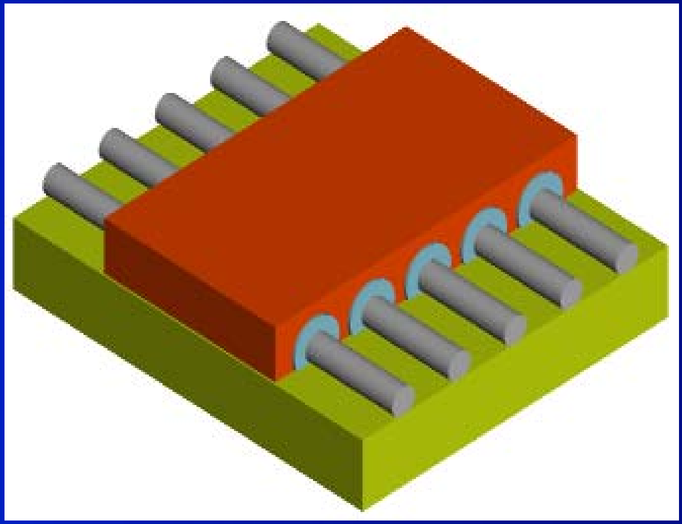
# Nanotube Electronics



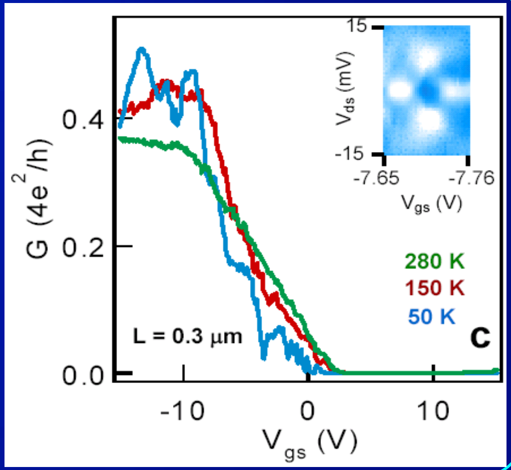

Si tri-gate transistor



SWNT tri-gate transistor

**Advantages of nanotube transistor…**

- No surface state.
- High carrier mobility or *ballistic transport*.
- Natural thin channel to minimize short channel effect.
- Unique geometry enabling better gate-channel capacitive coupling through "fringe field" of the surrounding dielectrics.




Ballistic nanotube FET (inset: Fabry-Perot-like interference pattern at T = 1.5 K, bright peak $G \sim 4e^2/h$)



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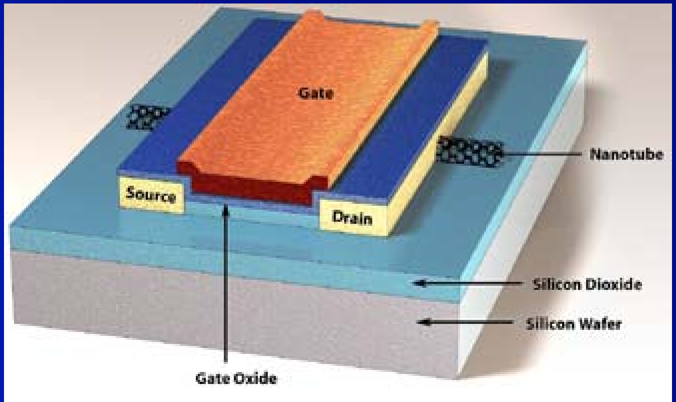
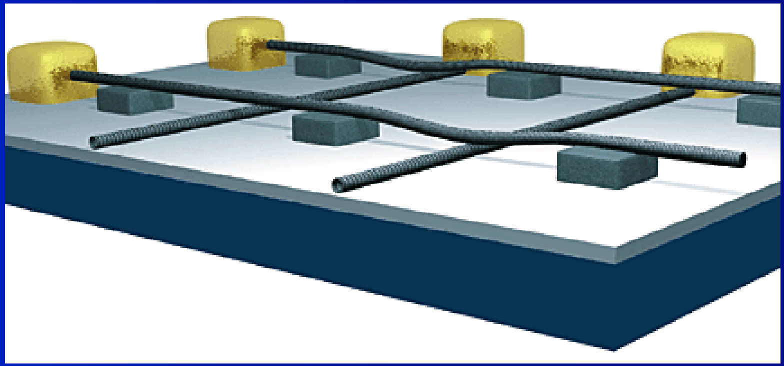
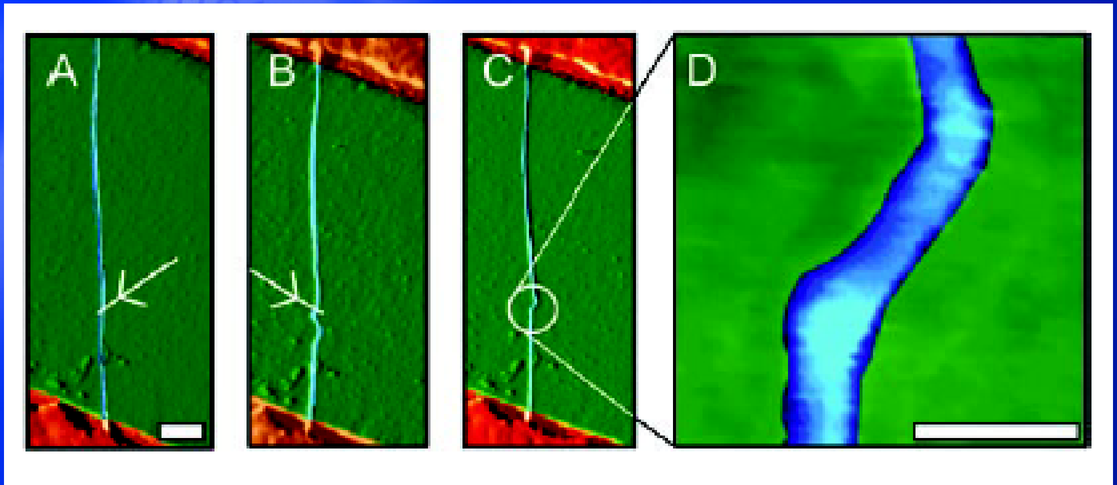
# Nanotube Electronics

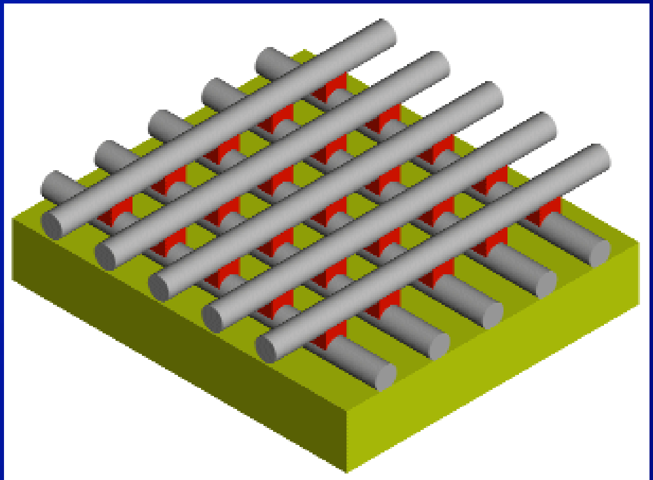
## Other Nanotube Opportunities

- ✓ Room-temperature single-electron transistor
- ✓ Optoelectronics
- ✓ Nano-electro-mechanical devices
- ✓ Interconnect
- ✓ Thermal interface materials
- ✓ Nano-sensors
- ✓ High density memory devices







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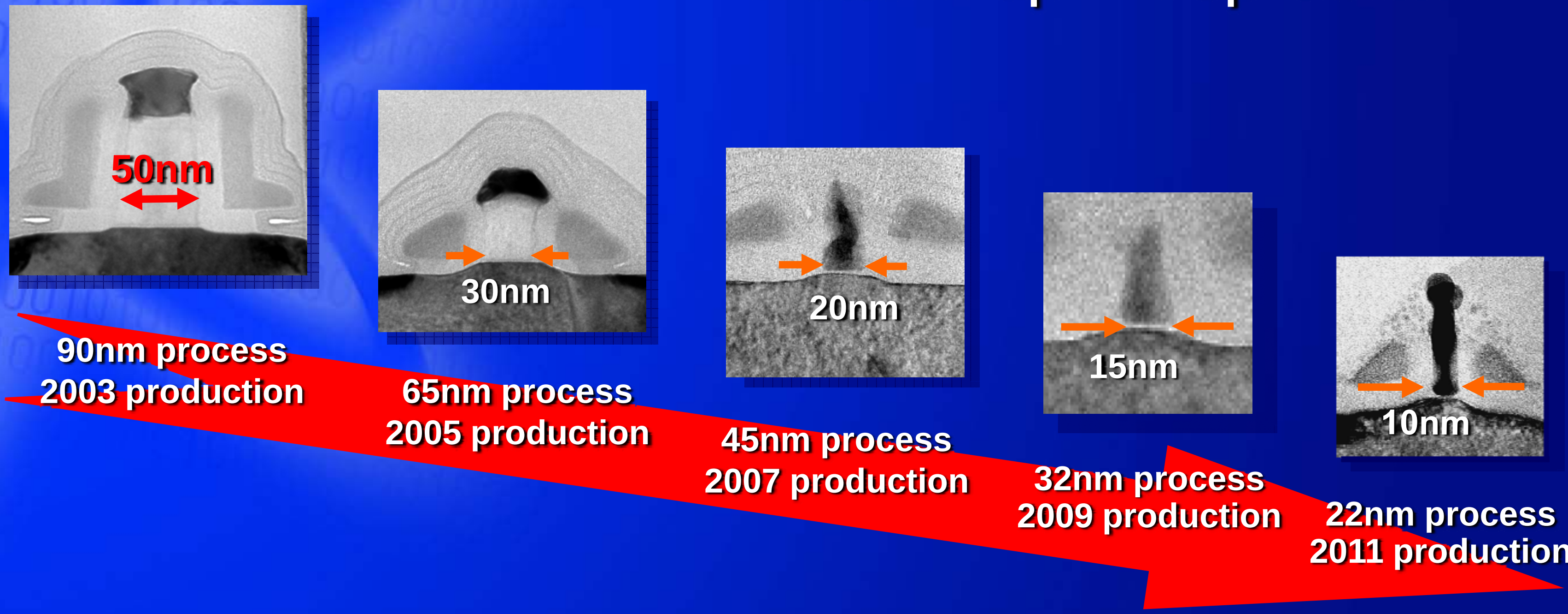
# How to Build Nanotube Chips?

Microchips ← Top-down method
Nanochips ← Bottom-up?
Top-down?
Bottom-up + Top-down?





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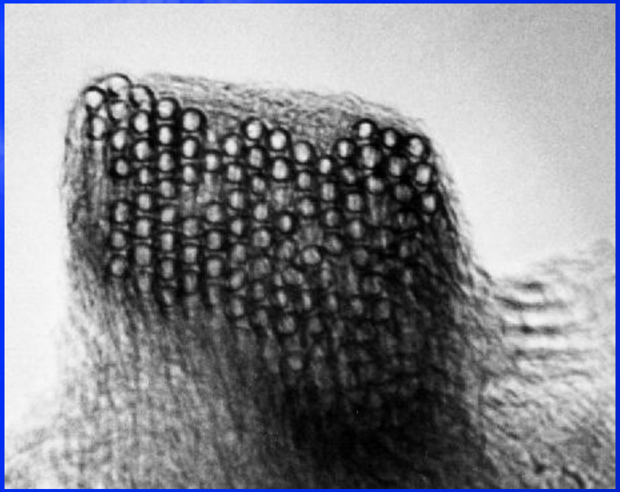
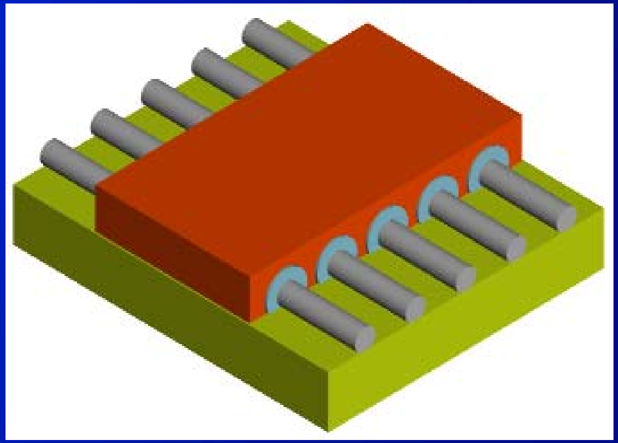
# Major Challenges for HVM of CNT Devices

- ✓ **Electronically pure material: precise property control**
  - – Pure metallic nanotubes for on-chip interconnection.
  - – Pure semiconducting nanotubes with a well-defined energy-gap for high performance transistors and memory devices.
- ✓ **Patterning technology: precise registry and orientation control**
  - – Array with regular spacing.
  - – Connection to electrodes.





SWNT tri-gate transistor

# Synthesis of Carbon Nanotubes

Arc Discharge

Laser Ablation

Chemical Vapor Deposition (CVD)

- ✓ Controllable process
- ✓ Direct growth on substrate
- ✓ Clean nanotubes
- ✓ Inexpensive

Type of nanotube:
- MWNT or SWNT

Diameter

Location

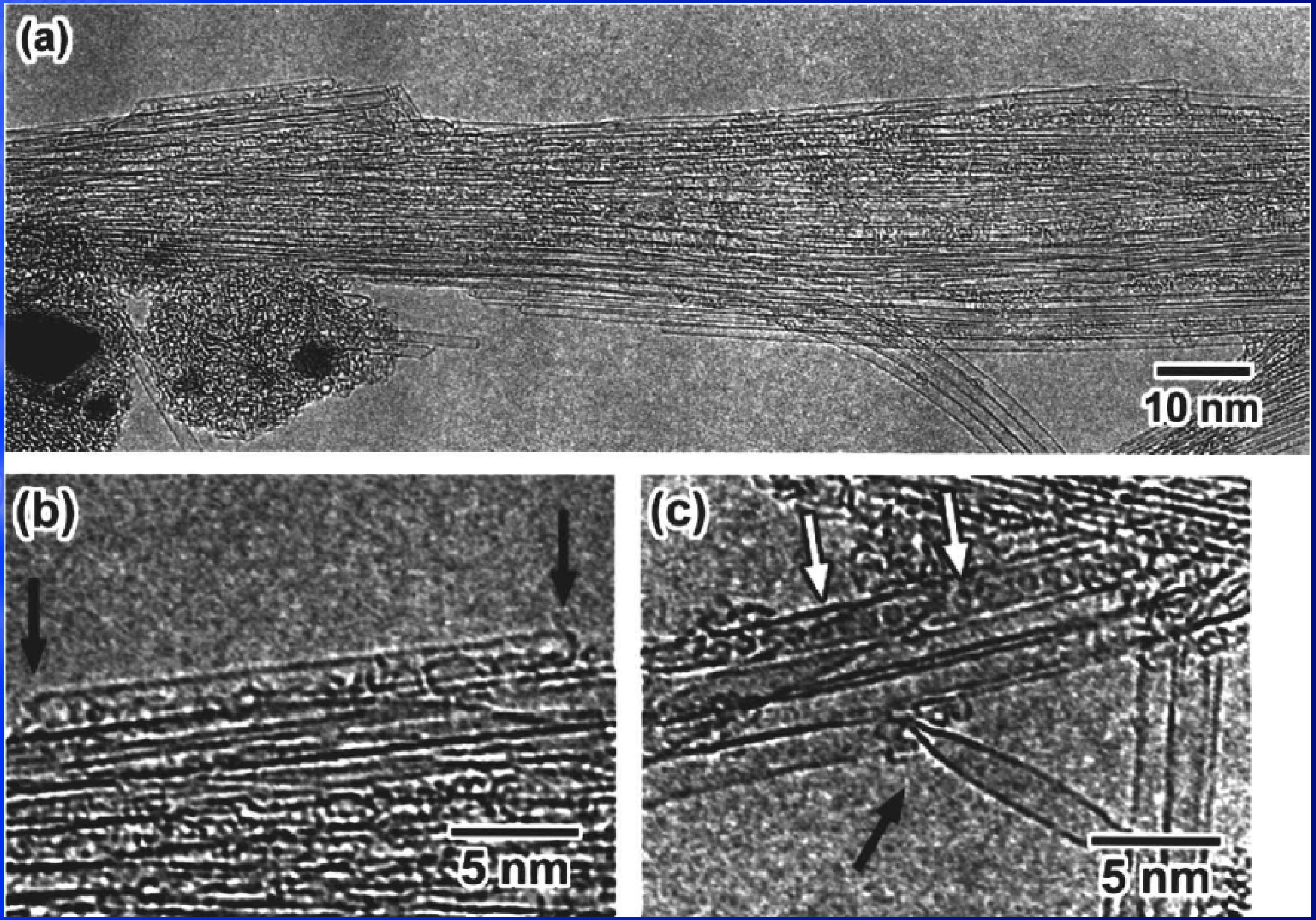
Orientation

Length

Chirality

- Metallic or semiconducting

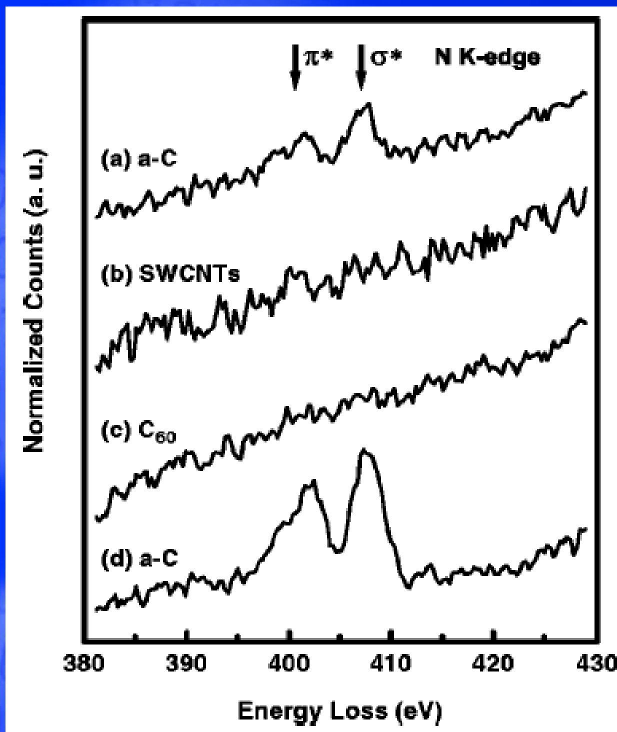
# Arc Discharge
## - HREM of SWNT and peapod structure

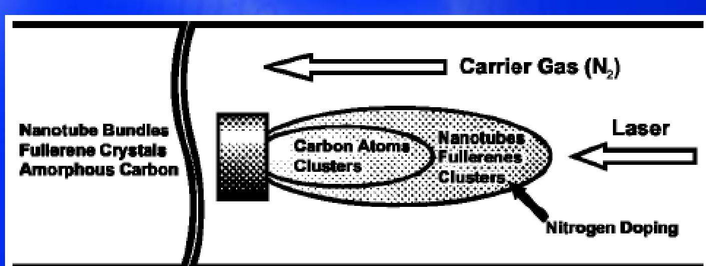


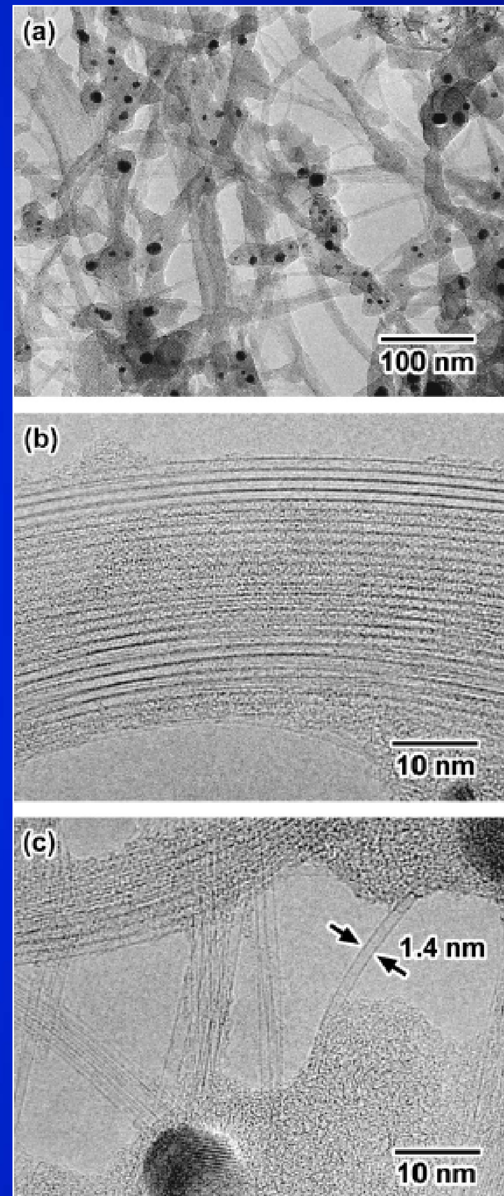

Y. Zhang et al., *Phil. Mag. Lett.* 79, 473 (1999)

# Laser Ablation
## - in nitrogen atmosphere

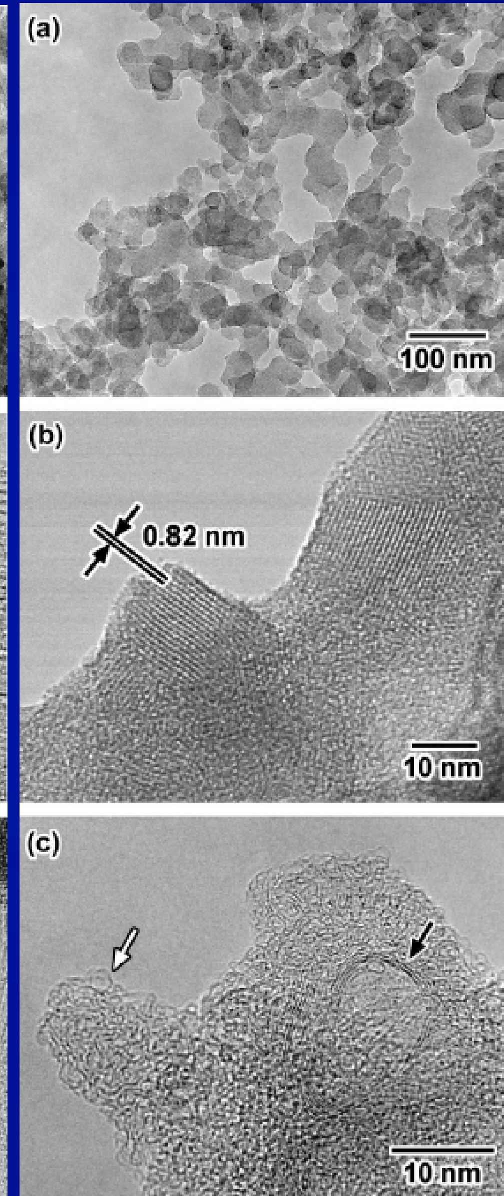
Y. Zhang et al., *Appl. Phys. Lett.* 73, 3827 (1998)




With NiCo catalyst

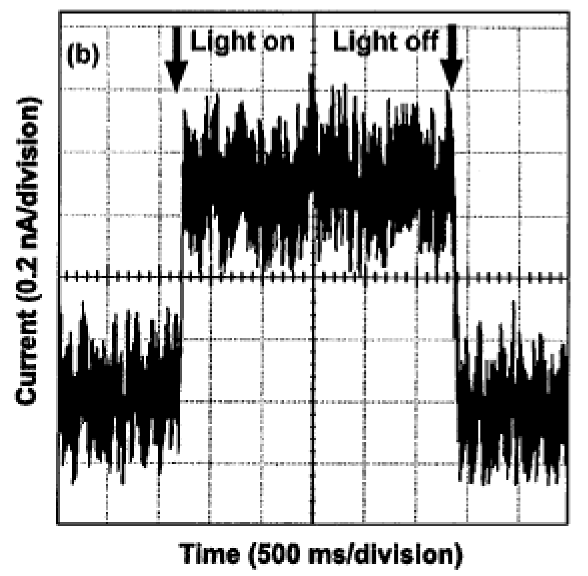


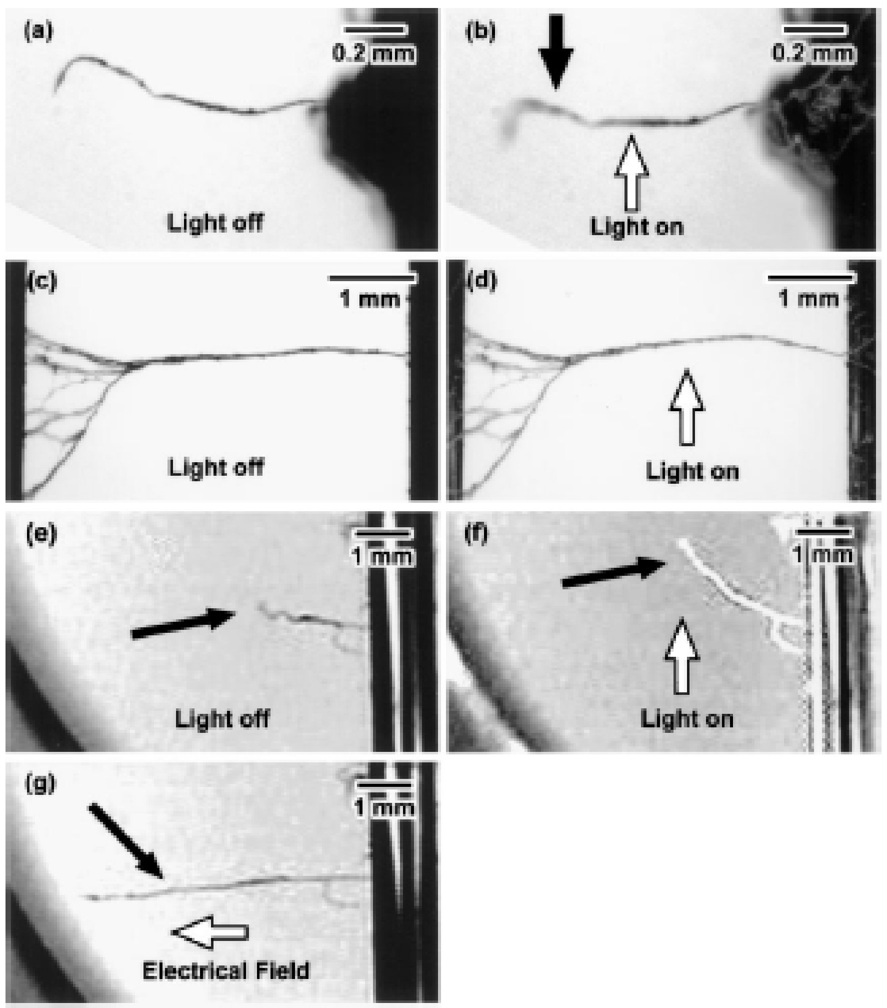

Without NiCo catalyst

# Exploring Exotic Nanotube Properties

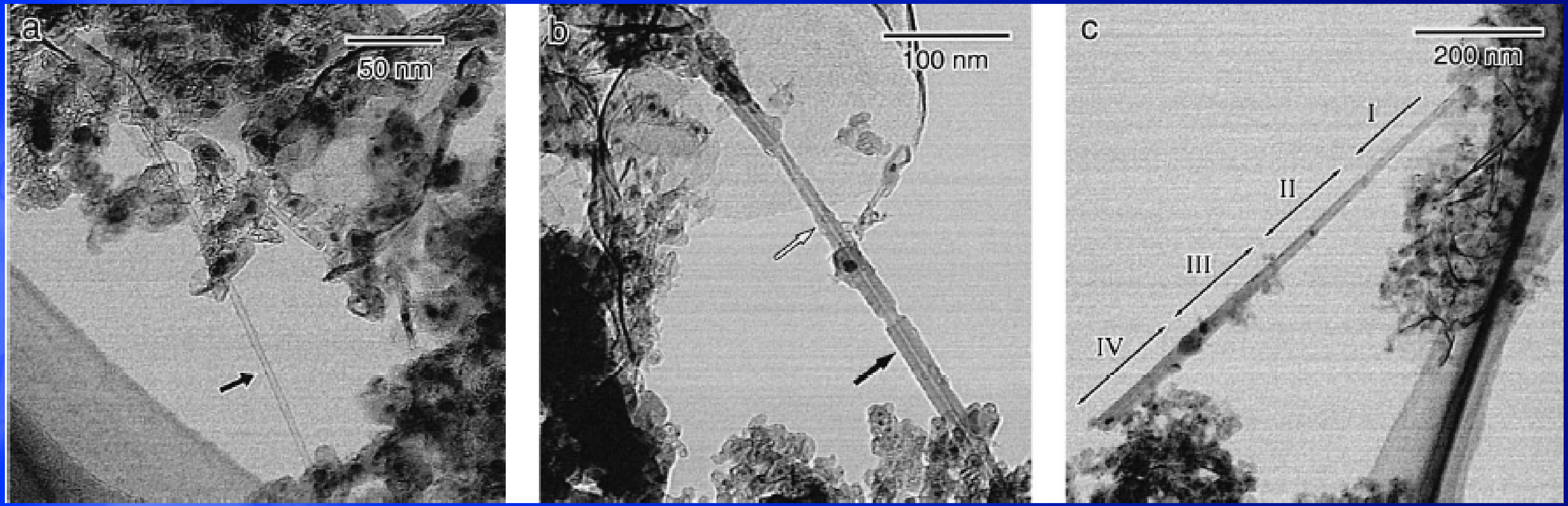
- Nanoelectromechanical System (NEMS)
- Optomechanical device
- Optoelectronics

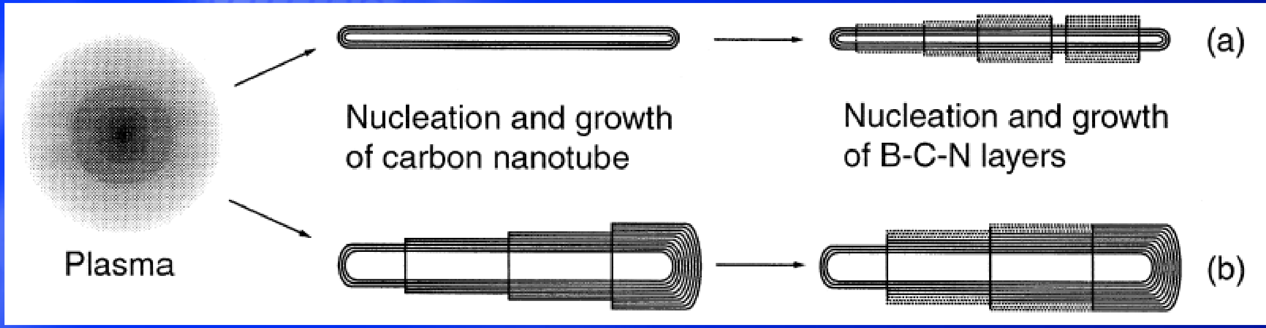
Y. Zhang & S. Iijima, *Phys. Rev. Lett.* 82, 3472 (1999)

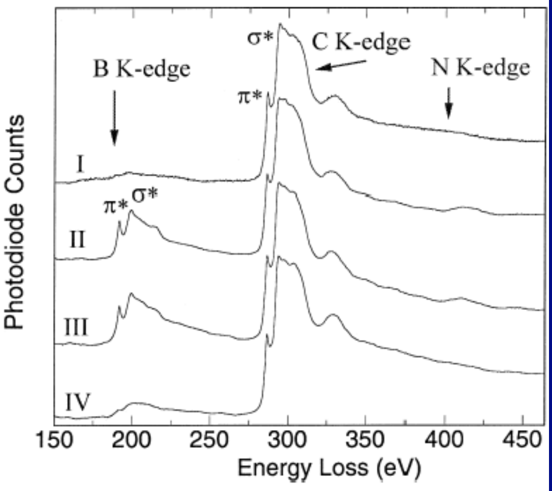


# Novel Heterostructured Nanotubes
## - BCN & C composite nanotubes



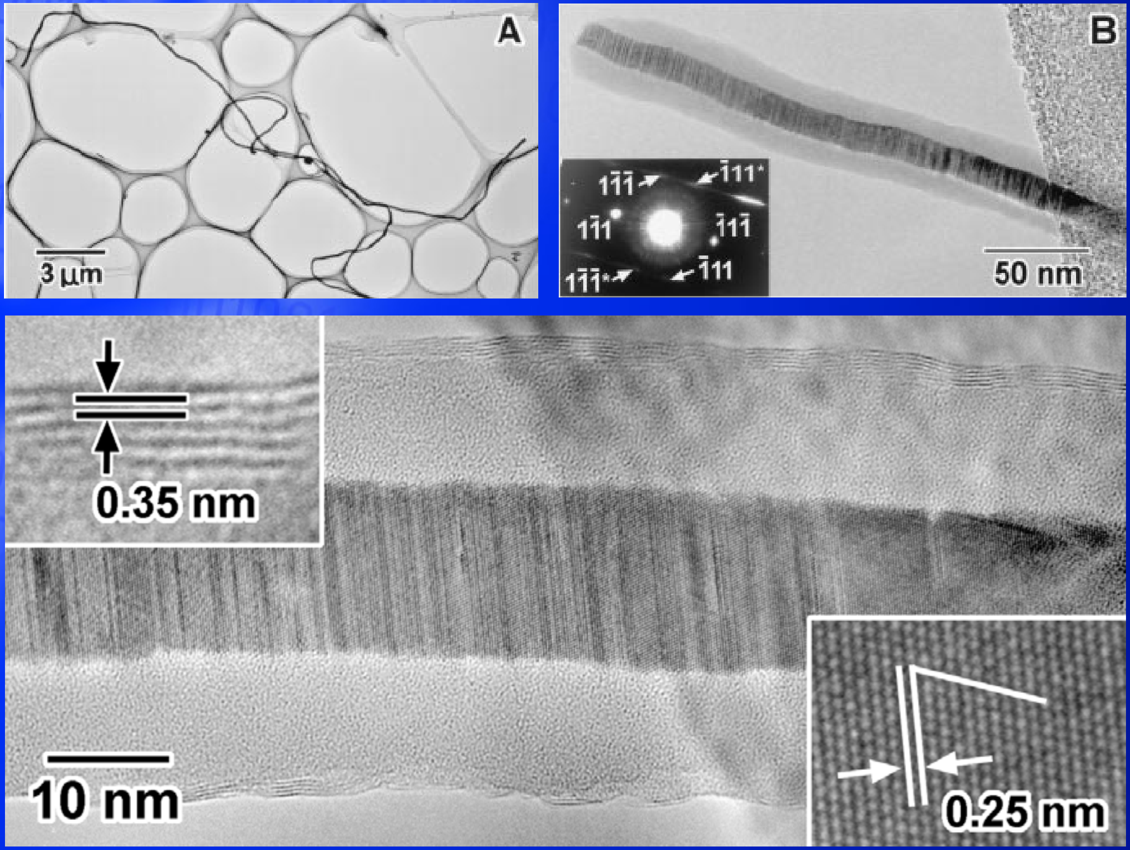



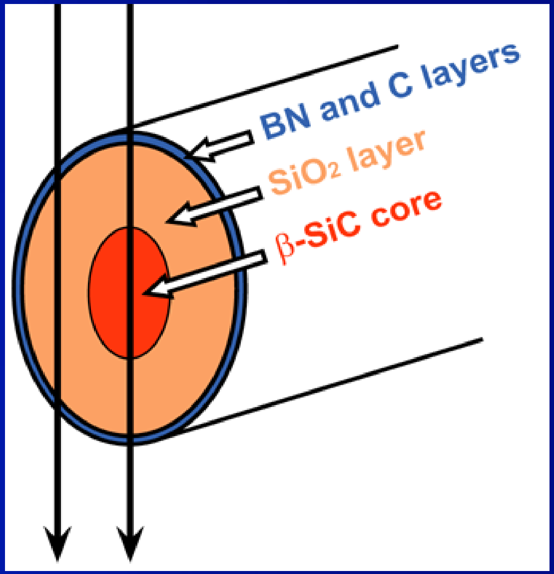



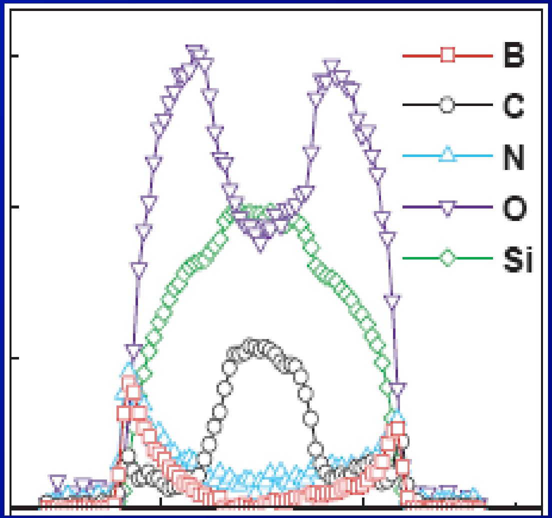

Y. Zhang et al., *Chem. Phys. Lett.* 279, 264 (1997).

# Novel Heterostructured Nanowires
## - Coaxial Nanocable

Y. Zhang et al., *Science* 281, 973 (1998)



# Controllable Synthesis of Carbon Nanotubes

Arc Discharge

Laser Ablation

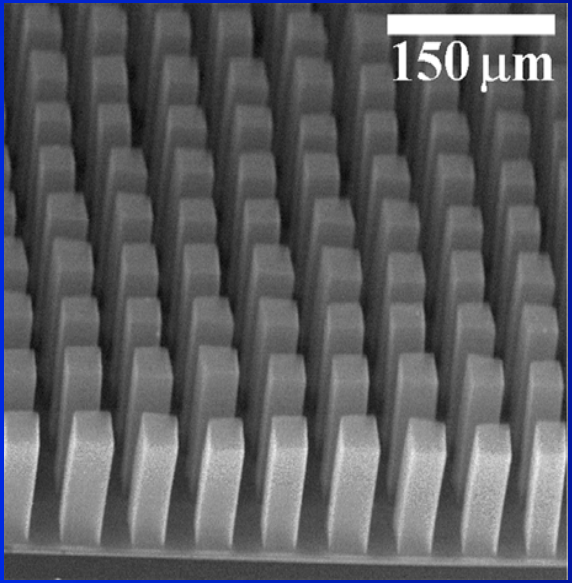
Chemical Vapor Deposition (CVD)

- ✓ **Controllable** process
- ✓ Direct growth on substrate
- ✓ Clean nanotubes
- ✓ Inexpensive

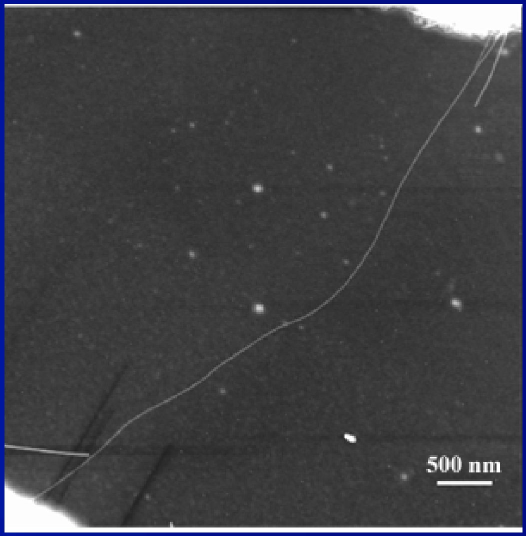
Type of nanotube:
- MWNT or SWNT
Diameter
Location
Orientation
Length
Chirality
- Metallic or semiconducting

# Controlling Nanotube Type

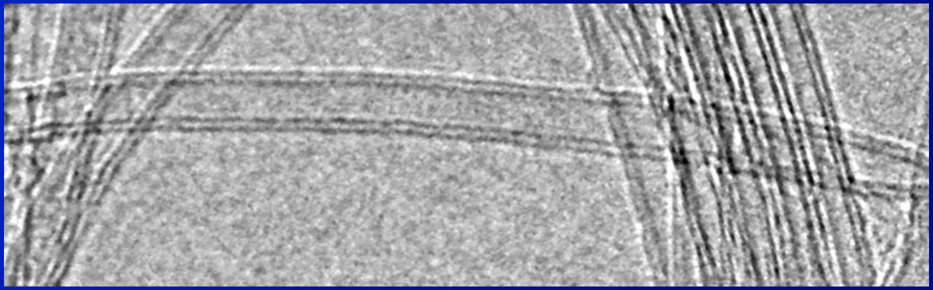
- Type of catalyst
  - Metal nanoparticle
    - Tube nucleation
  - Supporting materials
    - Make/disperse, keep nanoparticles
- Growth condition
  - Feedstock gas
    - Provide carbon
  - Carrier gas
    - Adjust reaction
  - Temperature
    - Decompose hydrocarbon
    - Anneal out defects




MWNT: $C_2H_4$, 700°C (Dai group)




SWNT: $CH_4$, 900°C

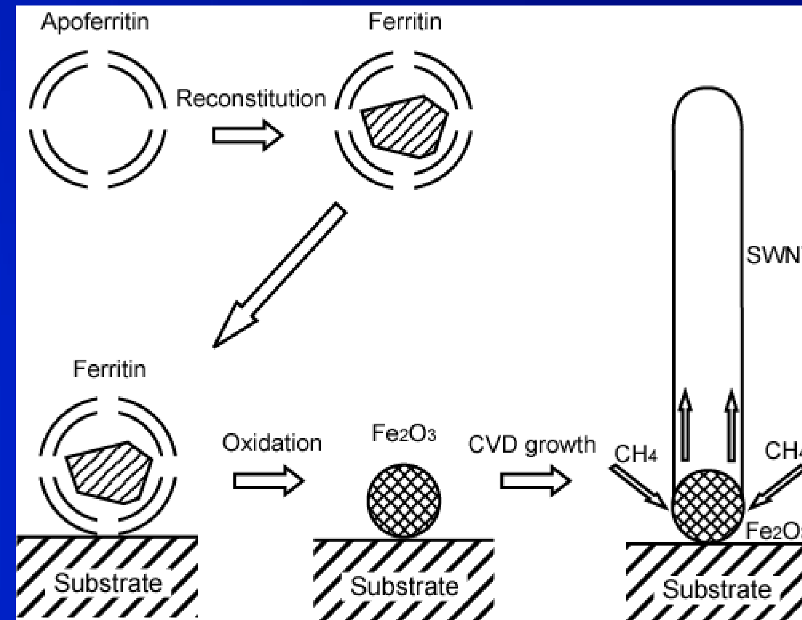


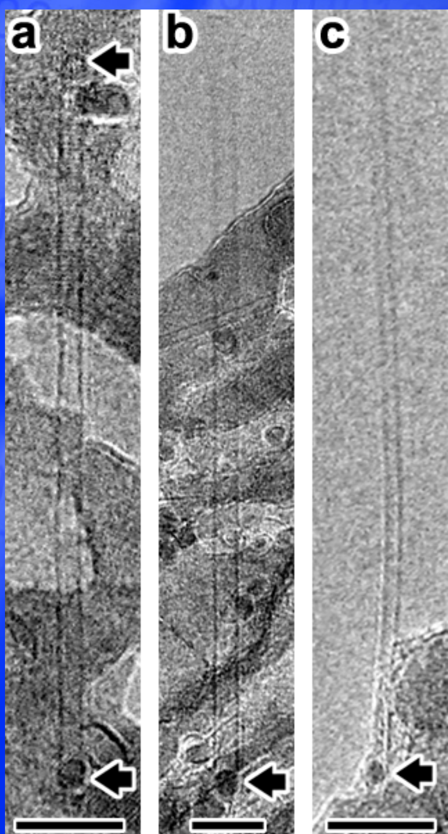
DWNT: $CH_4$+$H_2$, 900°C (Y. Zhang, unpublished data)

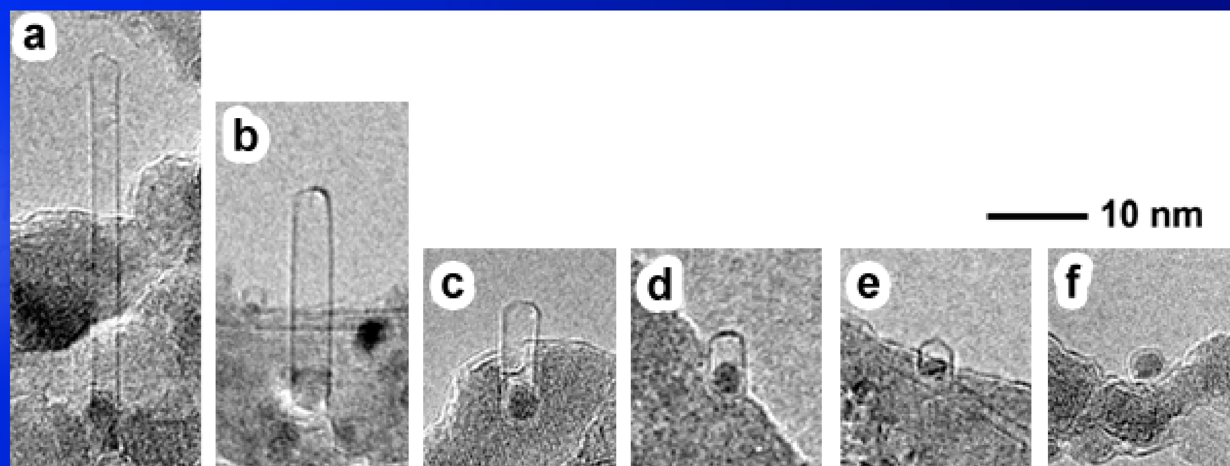
# Controlling Nanotube Diameter

- by controlling **nanoparticle** size

Y. Li et al., *J. Phys. Chem. B* 105, 11424 (2001)
Y. Zhang et al., *Appl. Phys. A* 74, 325 (2002)



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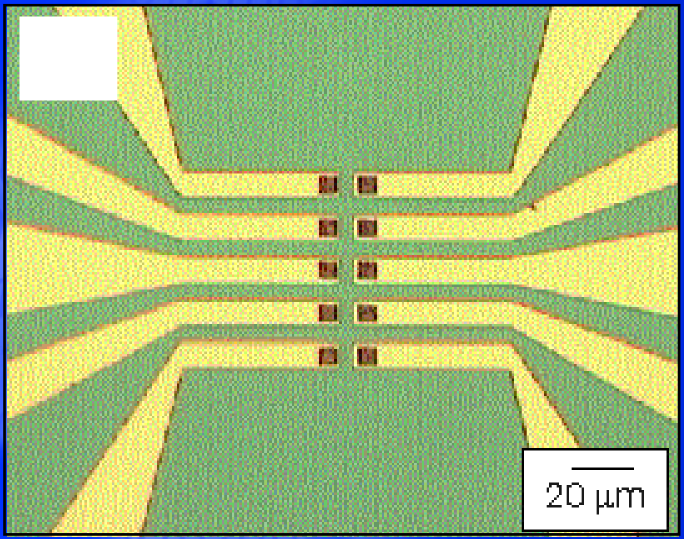
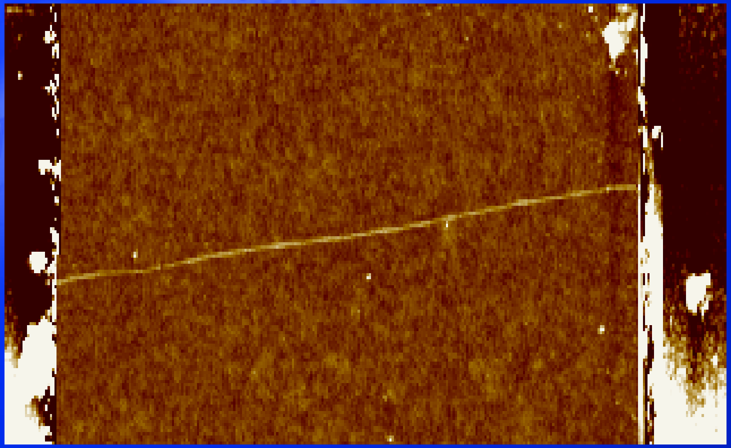
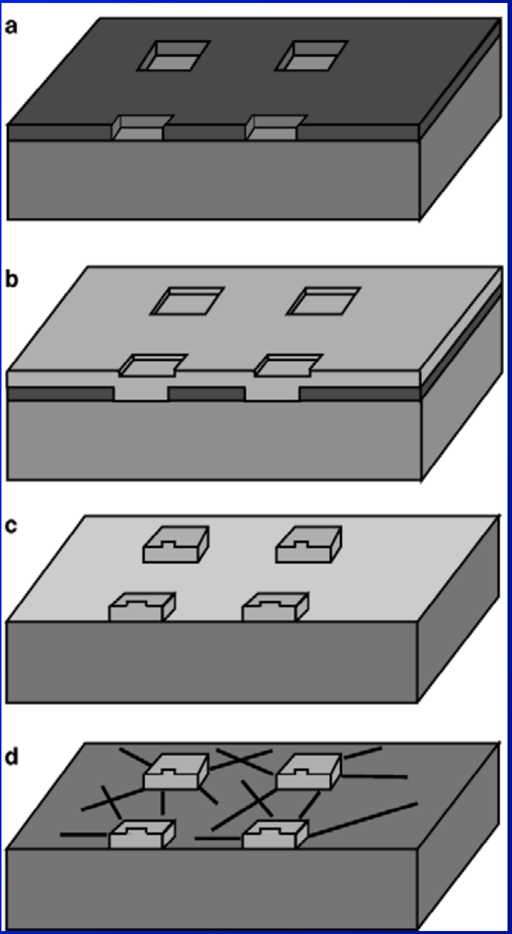
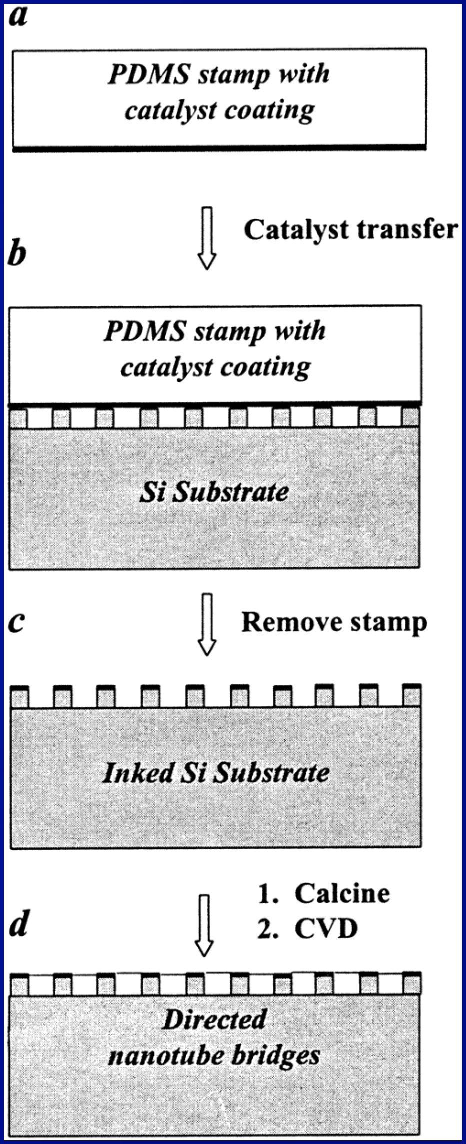
# Controlling Location

## – Catalyst Patterning





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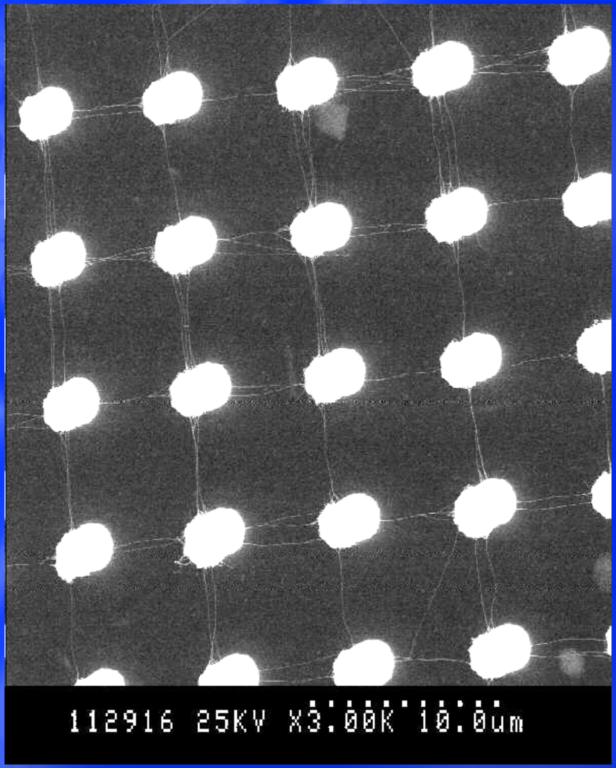
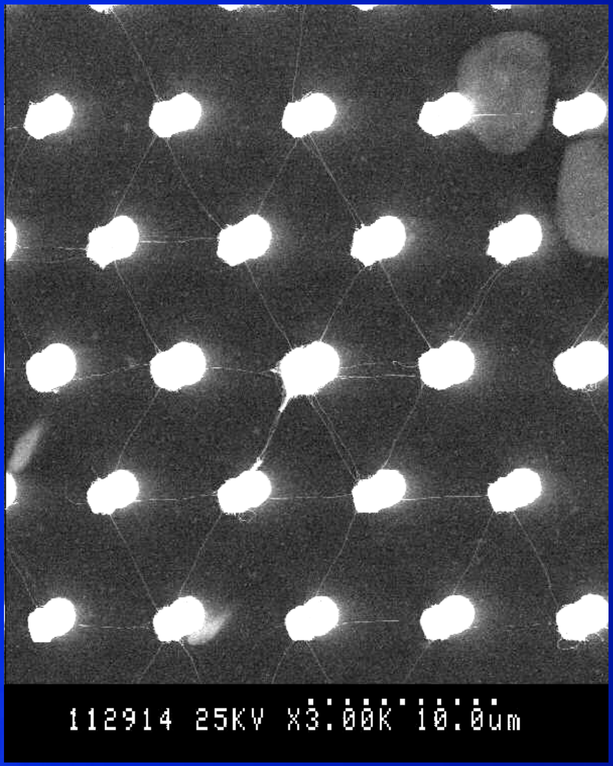
# Controlling Orientation - I

## - Self-directed Growth of Suspended SWNT

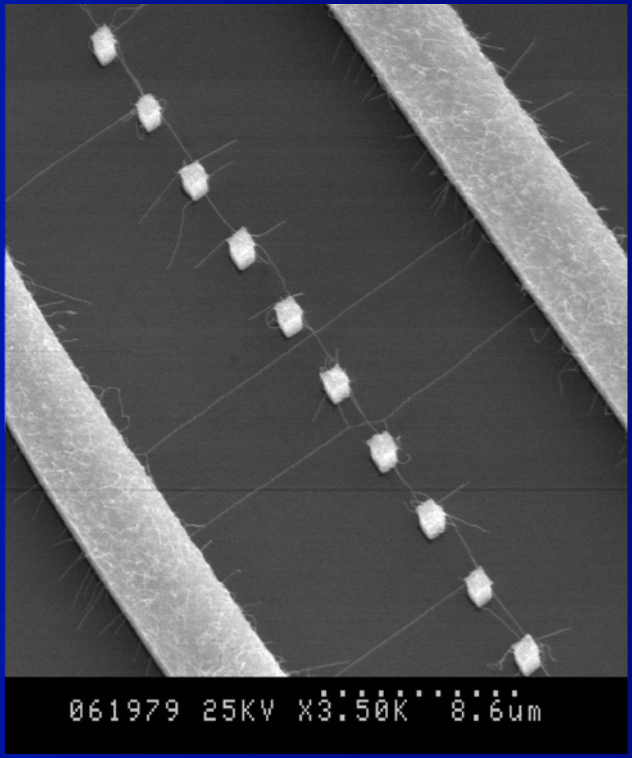
(Y. Zhang, unpublished data)




**Self-directed**




**Self-directed**

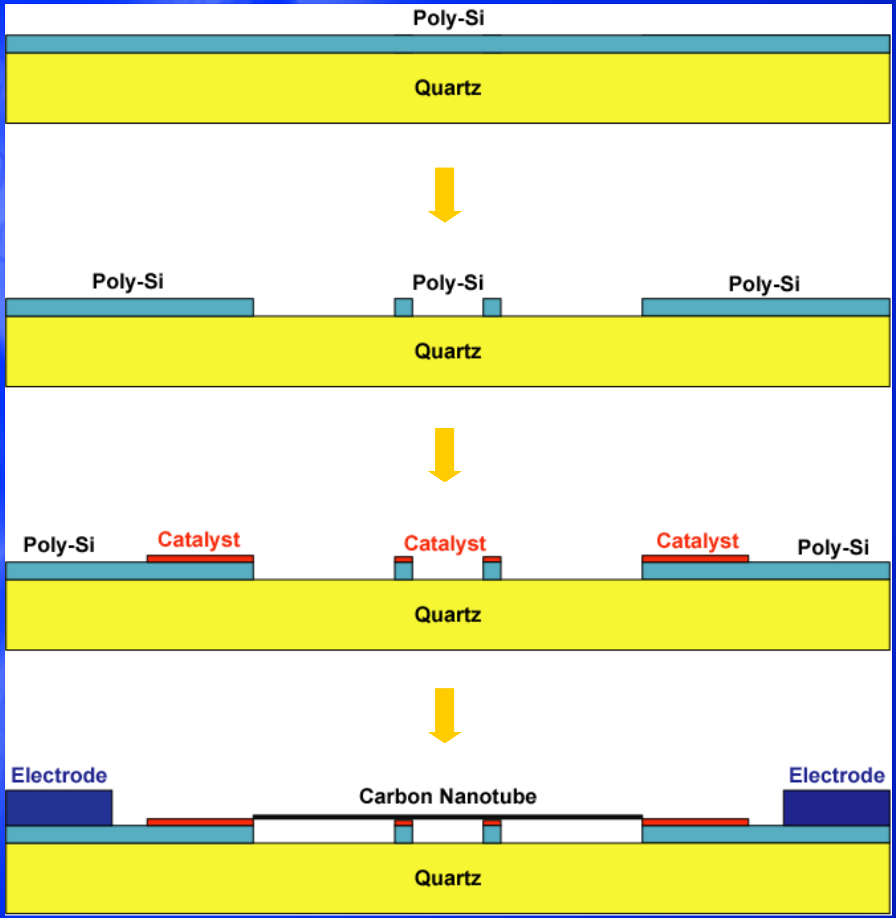


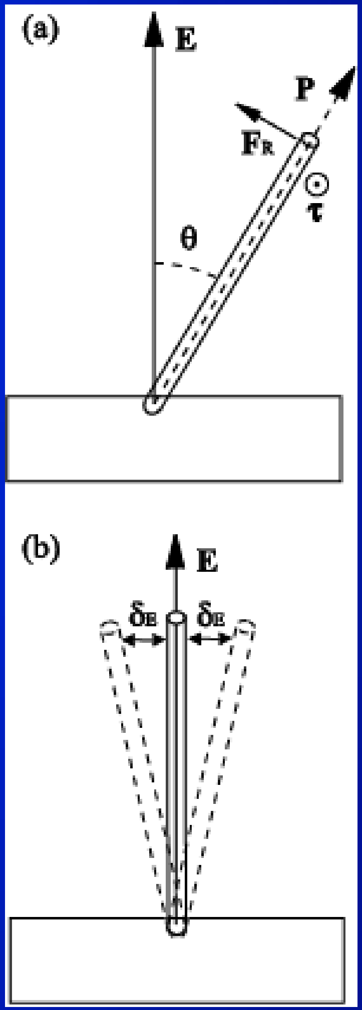

**Self-directed + E-field directed**

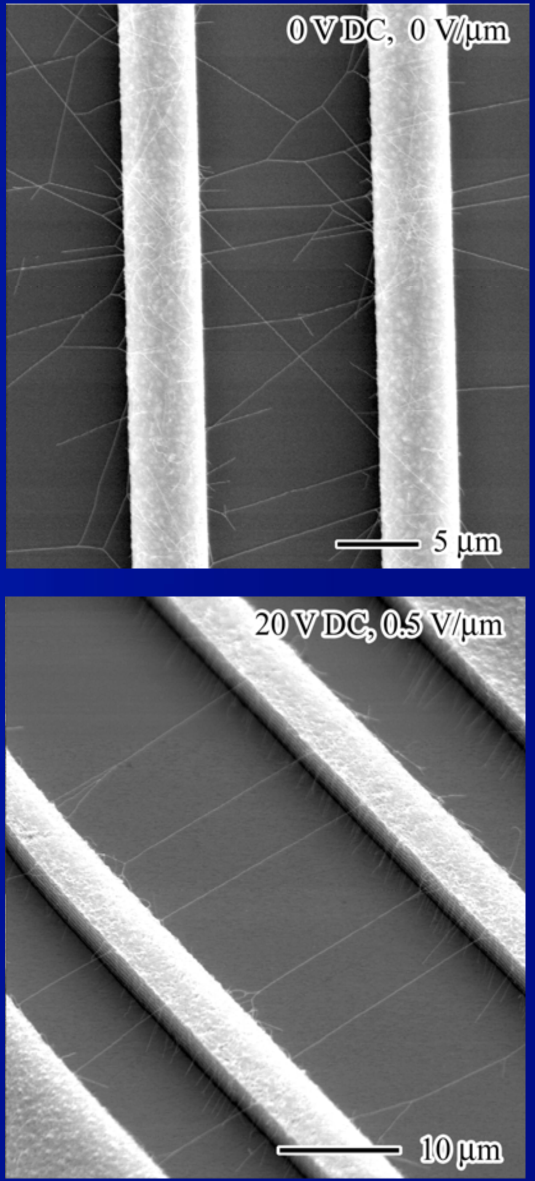
# Controlling Orientation – II

## - Electric-field-directed Growth

Y. Zhang et al., *Appl. Phys. Lett.* 79, 3155 (2001)



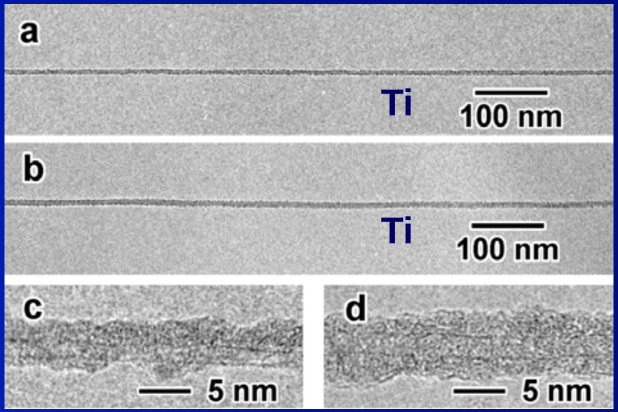
# Other Issues Regarding Nanotube IC

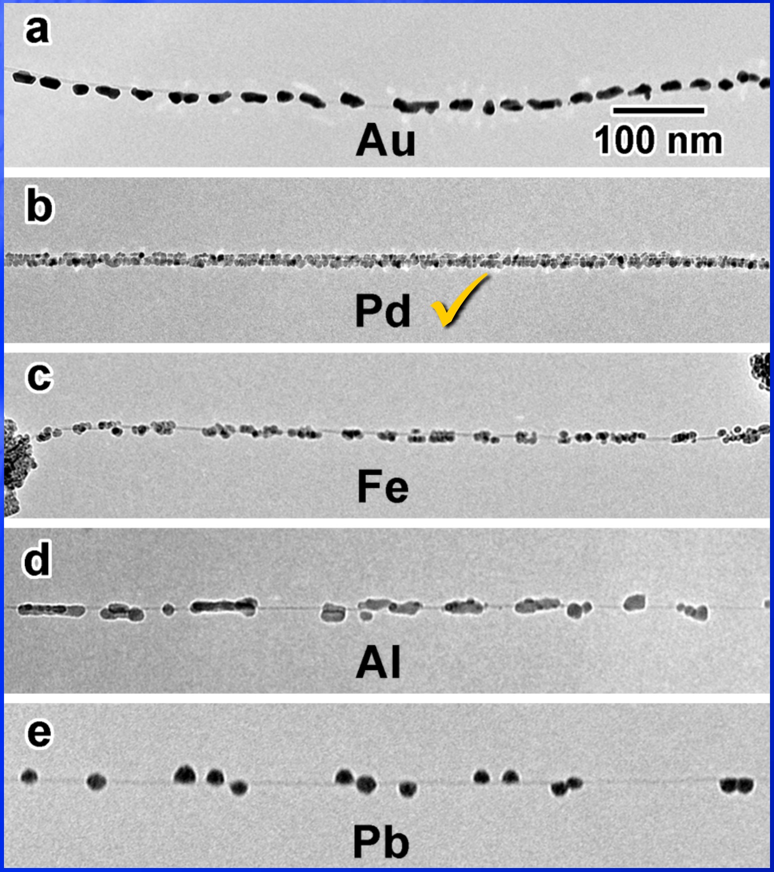
- Interconnection ✓
  - Ohmic Contact
- Doping
  - Intrinsic semiconducting nanotube?
- Environment
  - Why semiconducting nanotube is p-type?
  - Device stability
- Dielectric materials and Gate materials
  - Compatibility with nanotube IC

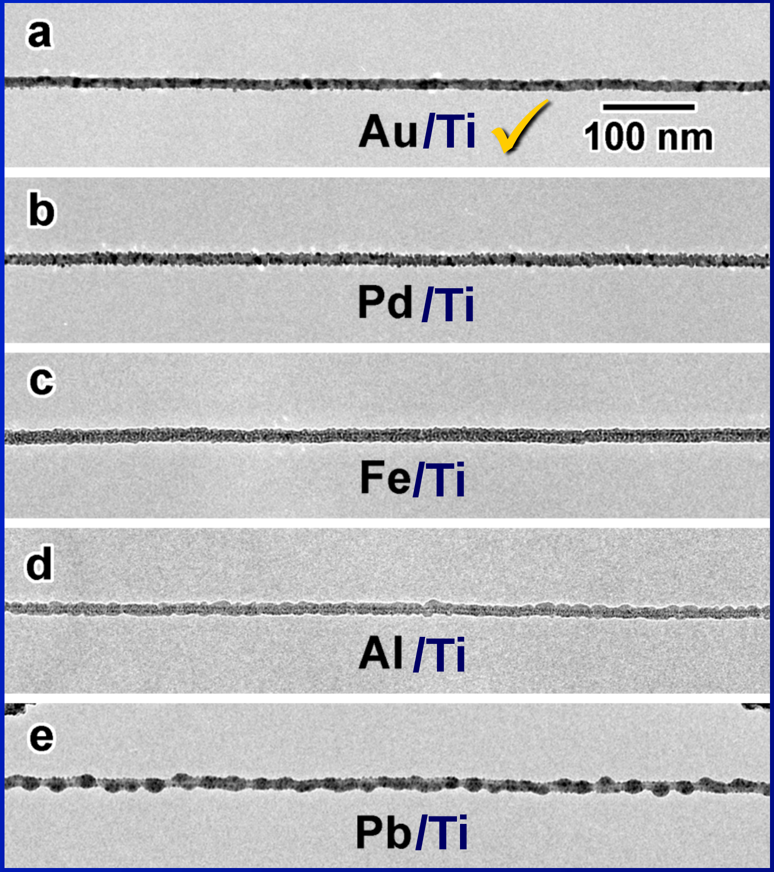
# Ohmic Contact

## - SWNT/metal contact

Y. Zhang & H. Dai, *Appl. Phys. Lett.* 77, 3015 (2000)
Y. Zhang et al., *Chem. Phys. Lett.* 331, 35 (2000)

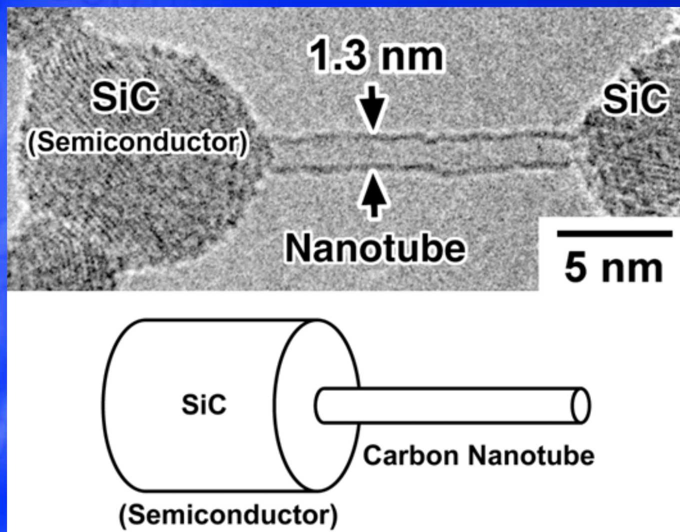


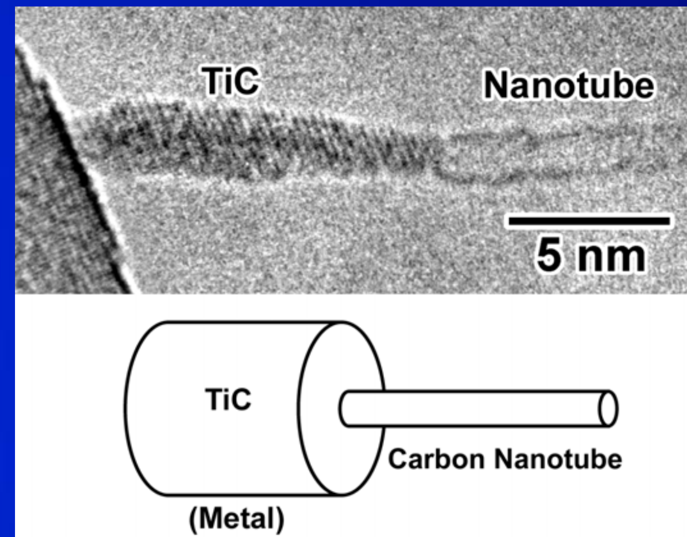



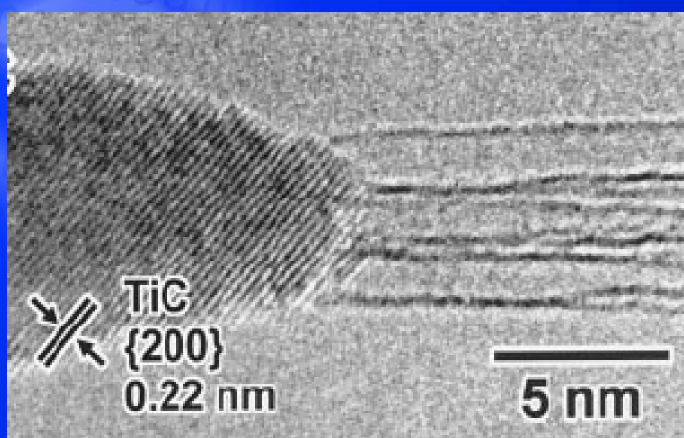



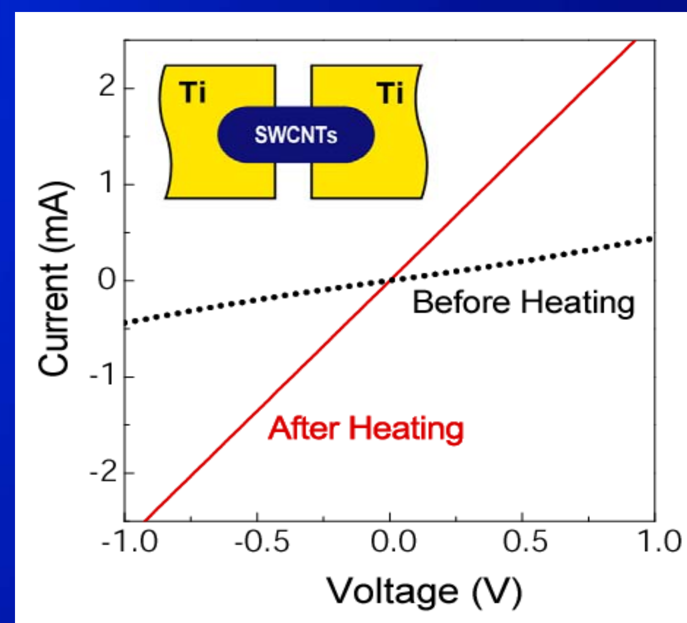
# Ideal Contact Solution

## - Nanotube-nanowire nanojunctions



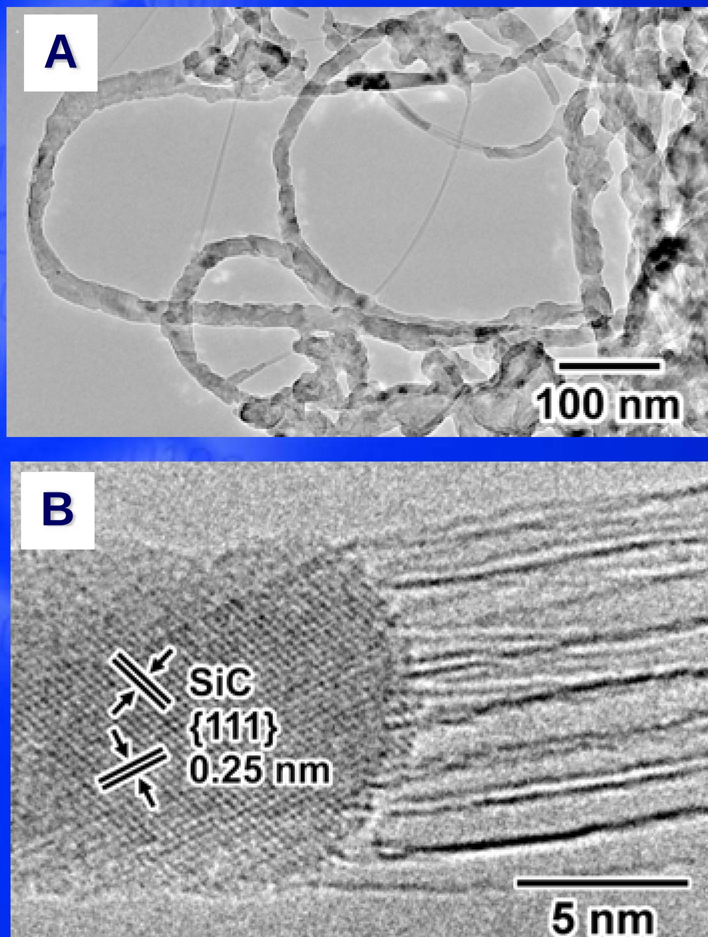



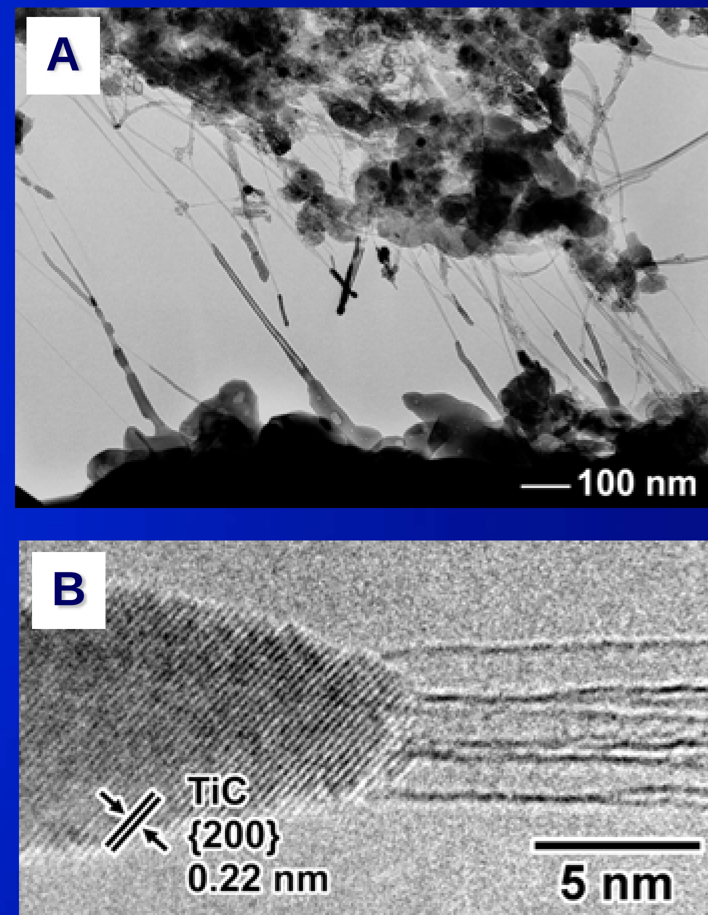

Y. Zhang et al., *Science* 285, 1719 (1999)

# Novel NT/NW Heterostructures
## - Nanowire and NW/NT Heterojunctions

Y. Zhang et al., *Science* 285, 1719 (1999)




SiC-SWNT



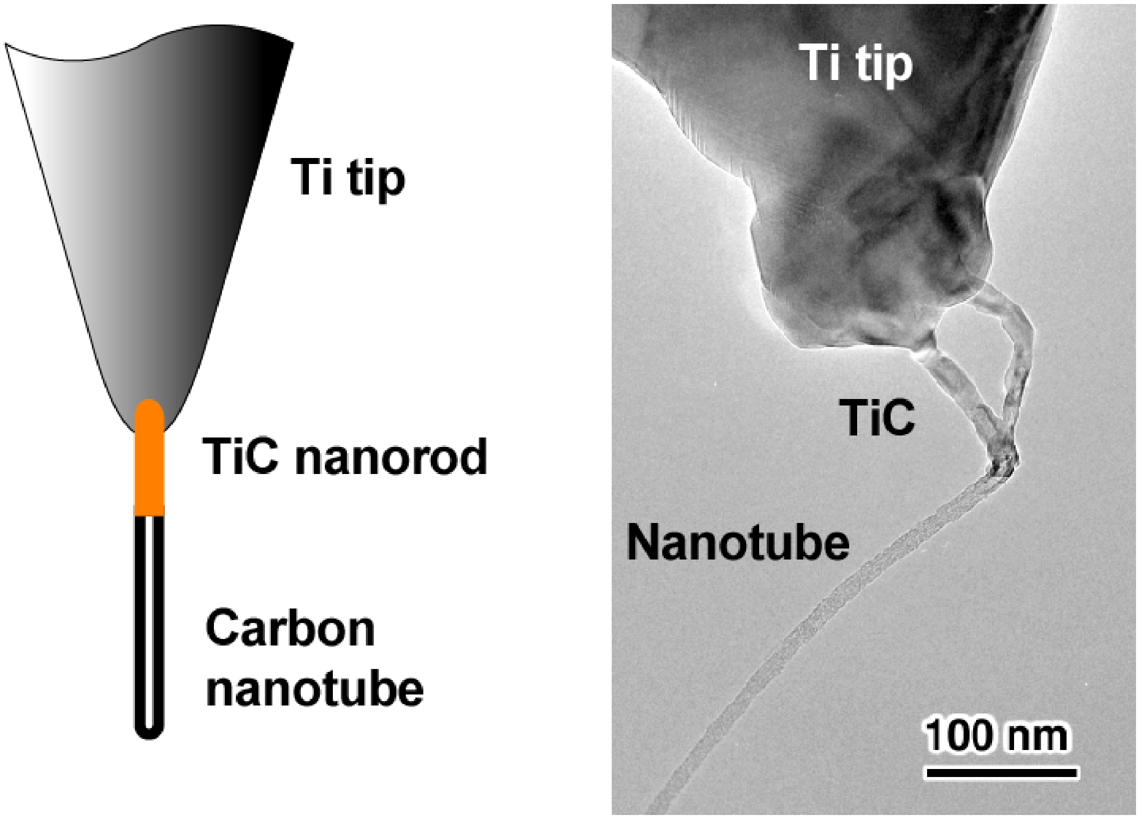

TiC-SWNT

# Novel NT/NW Heterostructures

## - Hybrid nanotube-nanowire devices

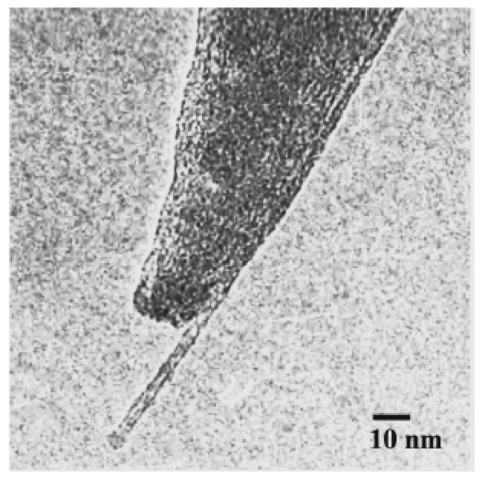
Y. Zhang et al., *Science* 285, 1719 (1999)

**Carbon Nanotube welded on a STM tip through TiC formation**



# Application: Probe-based data storage

IBM



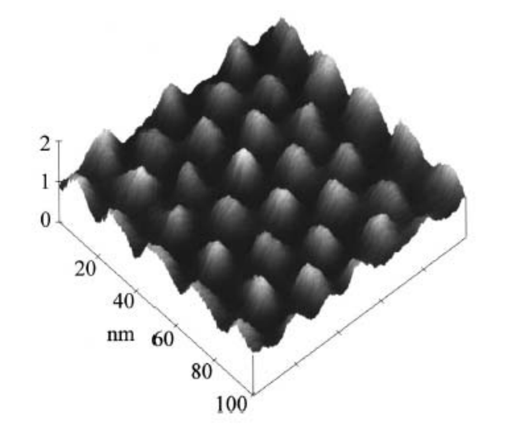
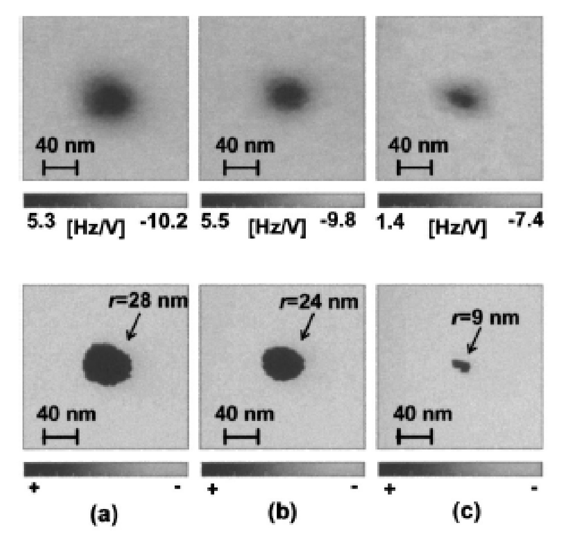
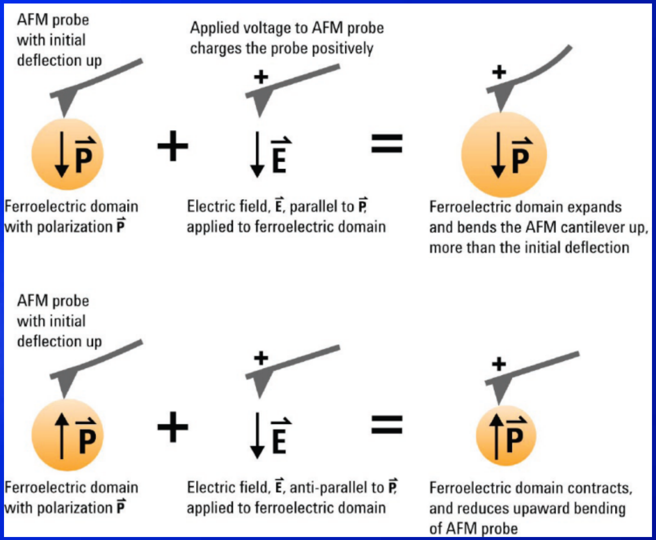



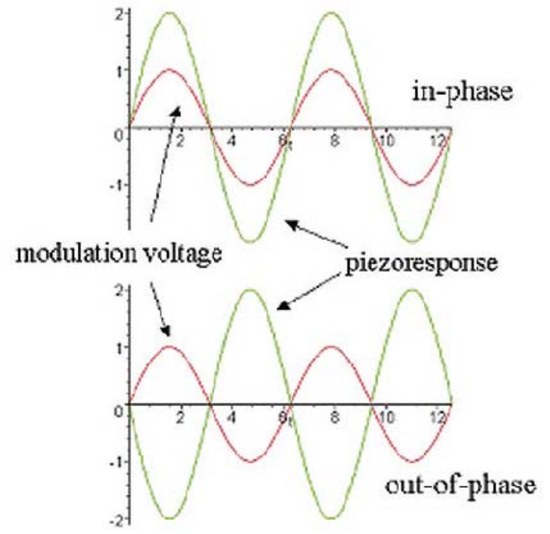

FIG. 4. 100 nm×100 nm×2 nm surface plot of ~8 nm bits with a ~1 nm titanium oxide height.

E. Cooper et al., Appl. Phys. Lett., **75, 3566 (1999).**



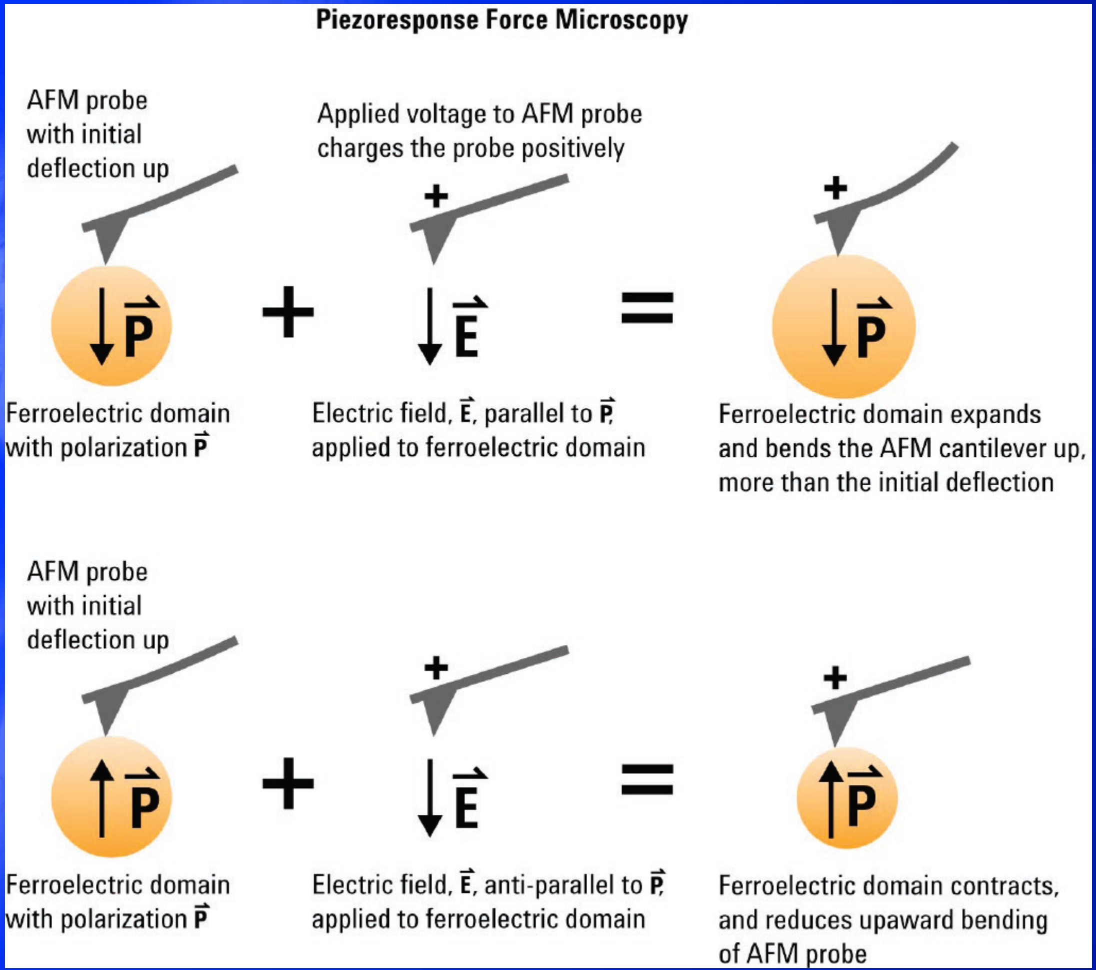

Y. Cho et al., Appl. Phys. Lett., **81, 4401 (2002).**

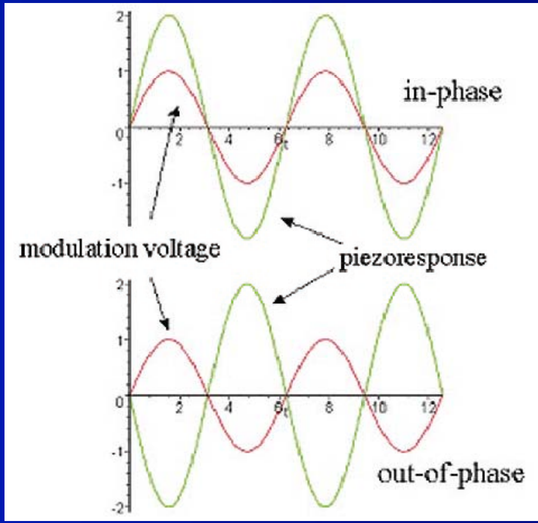


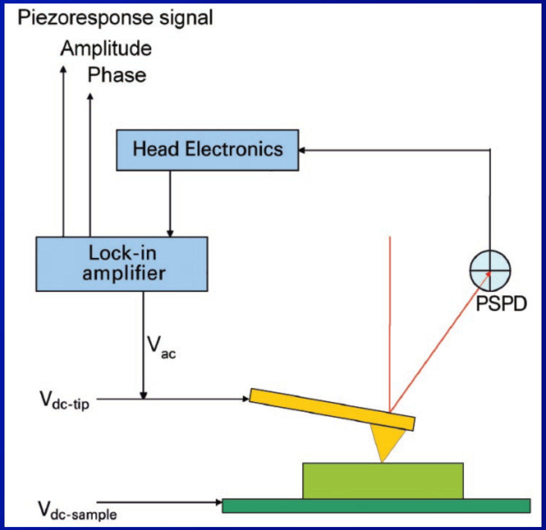




PFM: http://www.home.agilent.com/upload/cmc_upload/All/AN-PiezoRes_103107F.pdf

# PFM principles




•http://www.home.agilent.com/upload/cmc_upload/All/AN-PiezoRes_103107F.pdf



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# Advantage of using CNT probe

Small diameter → small recording bit size → high data storage density

Good electrical conductivity → electrical read/write

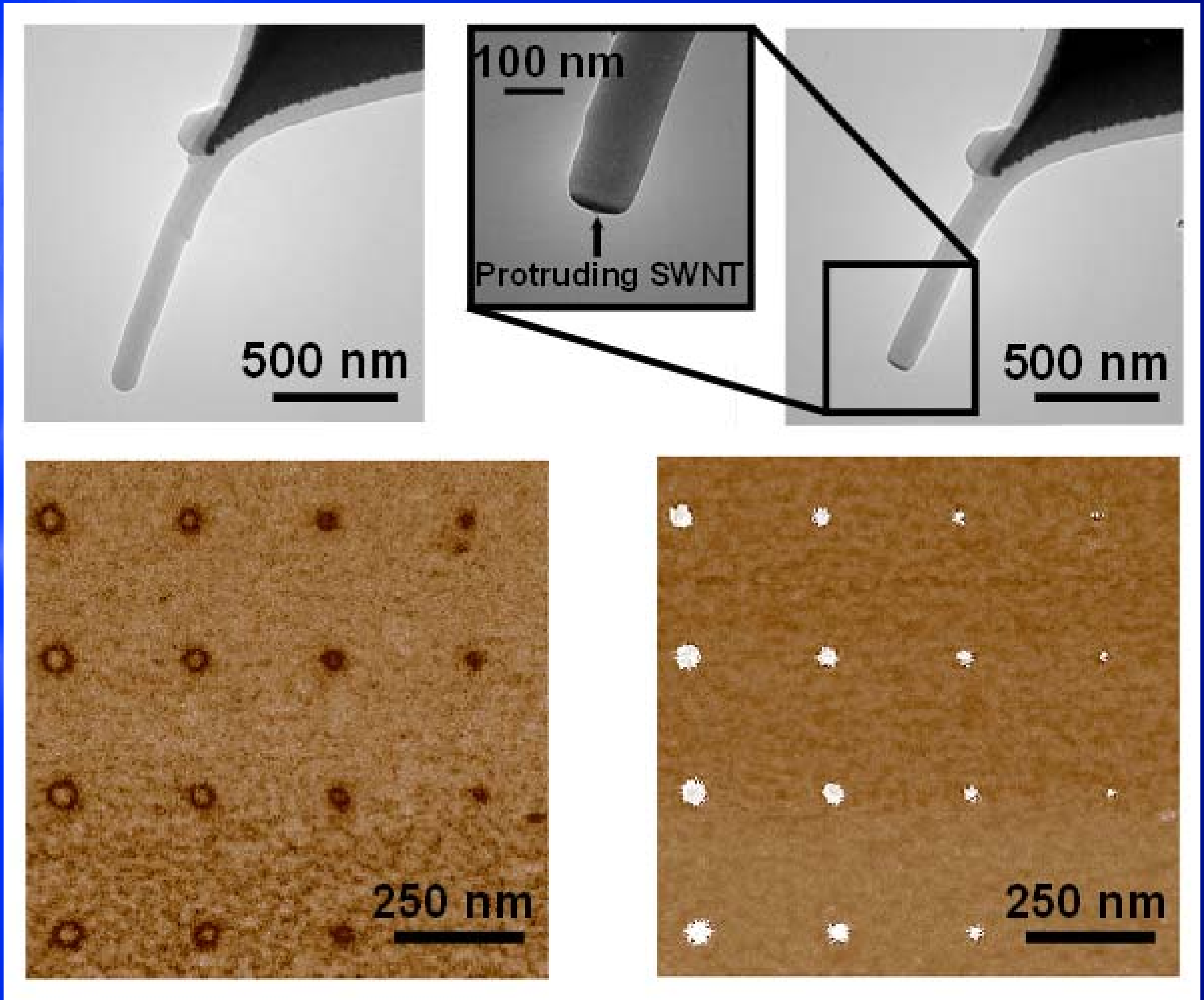
Good mechanical strength → low wear rate

High aspect ration → No degradation of resolution with wear → wear tolerant

Weak Point: buckling for long tubes, especially for SWNTs, under contact mode operation

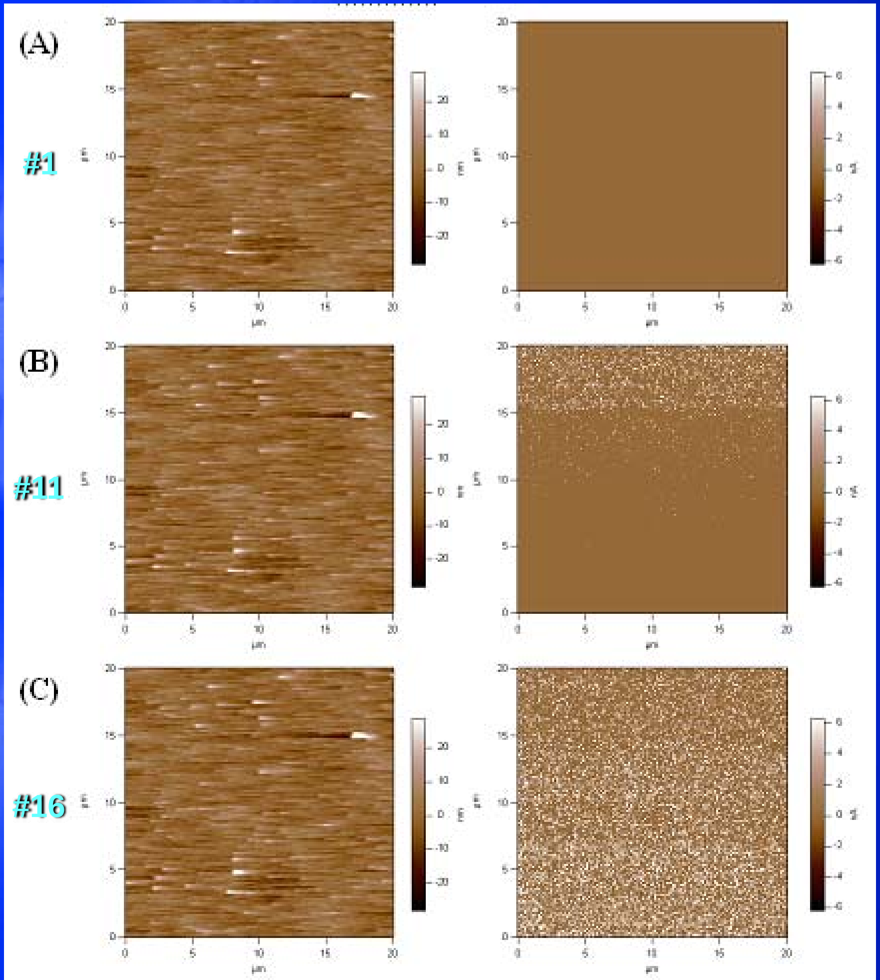
- Solution: dielectric enhancement: keeping small electrical contact; much stronger for contact mode operation.

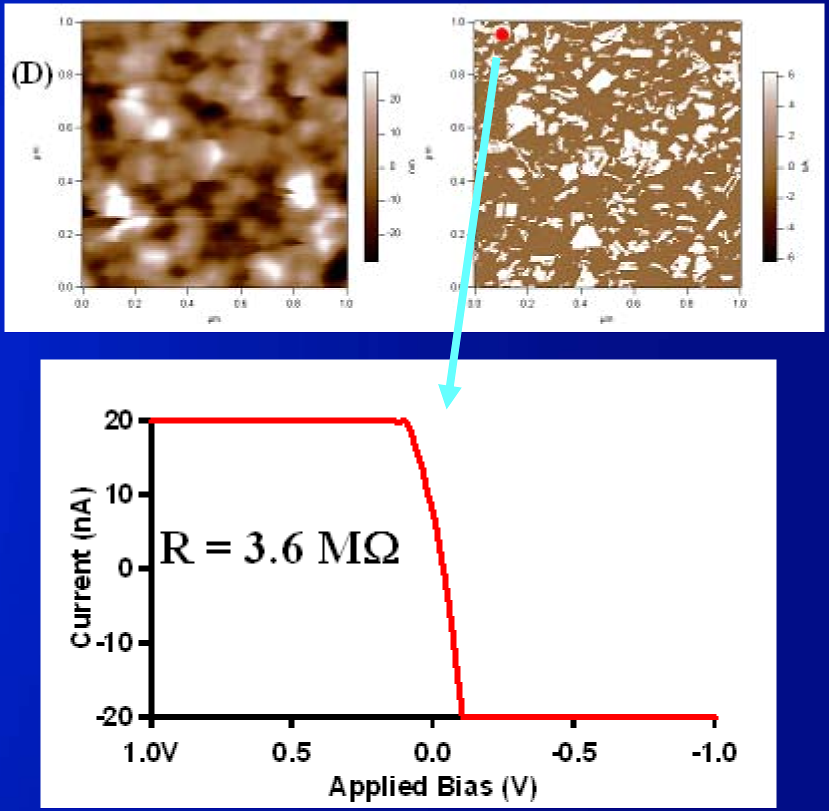
# Nanopencil W/R on ferroelectric media




N. Teyabi et al., Appl. Phys. Lett. 93, 103112 (2008)

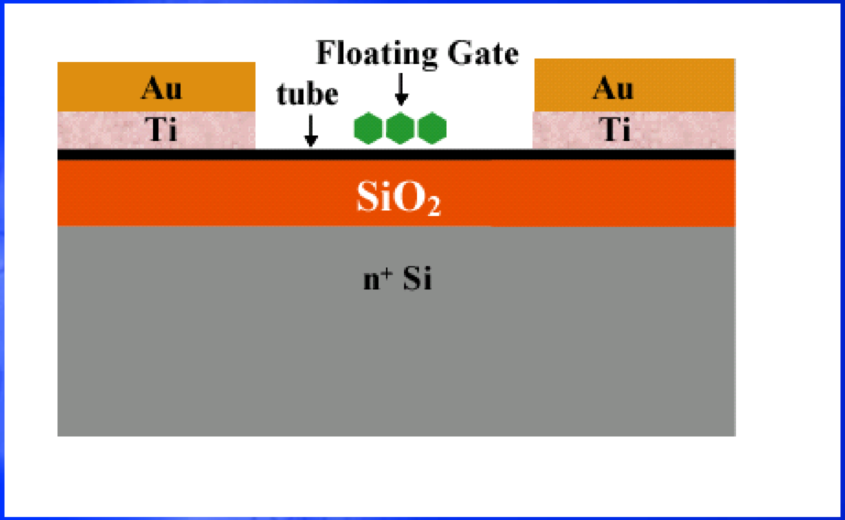
# Sharpening Nanopencil

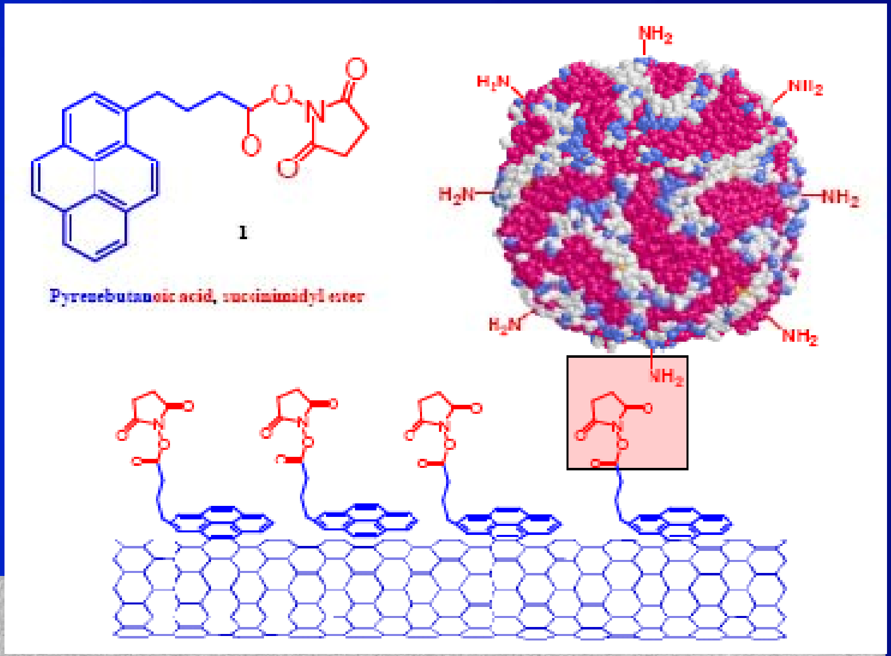


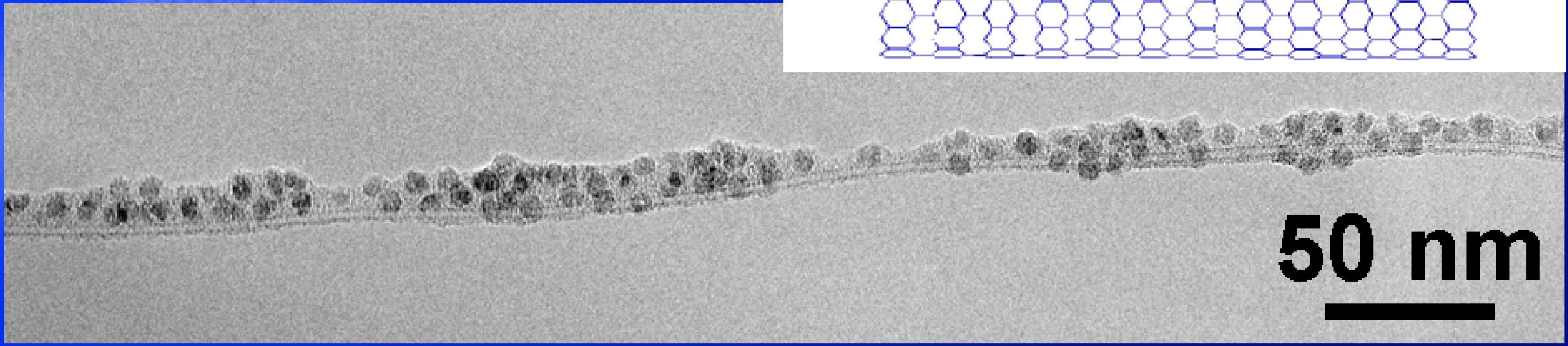




N. Teyabi et al., *Appl. Phys. Lett.* 93, 103112 (2008)

# Application:
# 0D-1D System : Ultra-Sensitive Charge Sensor
## – Biosensor and Single-Electron Memory Devices



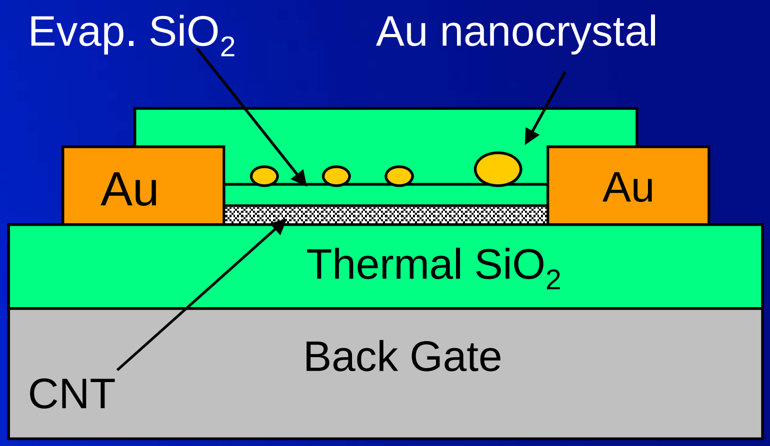



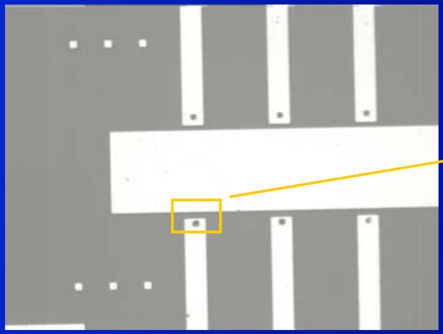

Noncovalent sidewall functionalization of single-walled carbon nanotubes for protein immobilization
R. Chen, Y. Zhang, D. Wang, H. Dai, *J. Am. Chem. Soc.* 123, 3838 (2001).

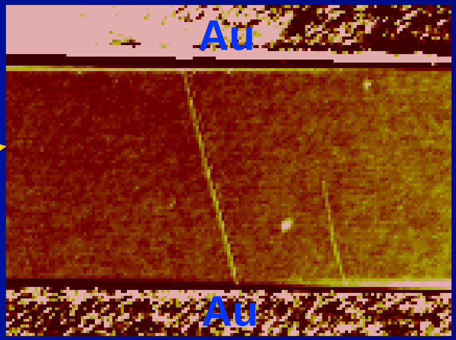
# Prototype CNT-QD Device

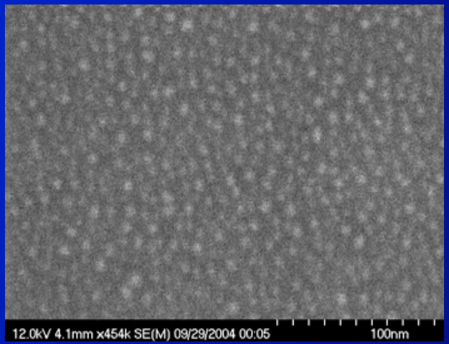
- Back gated carbon nanotube FET (CNTFET) – Prior art
  - Degenerately doped Si
  - 100 nm thermal gate oxide
  - 5nm Cr / 50 nm Au source/drain
- NV-memory: Superstructure on CNFET containing innovation:
  - Deposit 5 nm evaporated $SiO_2$
  - Deposit Au thin film and form nanocrystals
  - Cap the device with 30 nm PECVD oxide
  - Etch (RIE) open the pads for electrical measurements

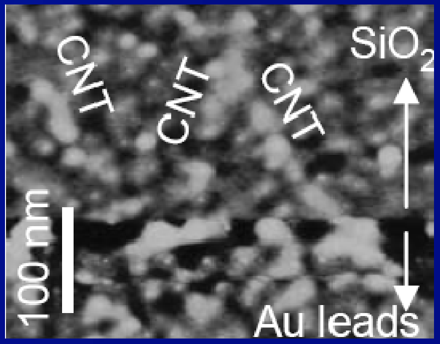
**U. Ganguly et al., *Appl. Phys. Lett.* 87, 043108 (2005)**





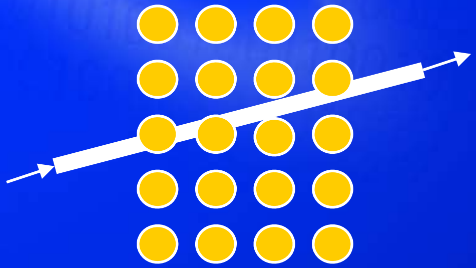
# Nanotube (1D) vs Si (2D) for nano-floating gate memory

## Electrostatics due to nanocrystals:

Charged nanocrystals produce an egg-crate like potential well structure on the plane below or above

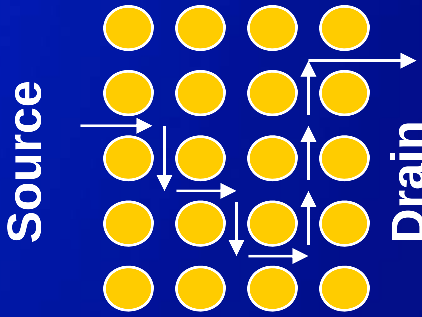
**Nanotube based FET**

- Cylinderical approximation for capacitance calculation – improved electrostatic coupling with gate – low r/w voltage.
- 1D electron system
- Transport in 1D – no percolation
- Electron is confined to nanotube and cannot circum-navigate around barriers
- High charge sensitivity



**Planar silicon-based structures**

- Parallel plate approximation for capacitance calculation
- 2D electron gas under inversion
- Transport governed by percolation
- Charge feels minimal potential during transport
- Minimal charge sensitivity



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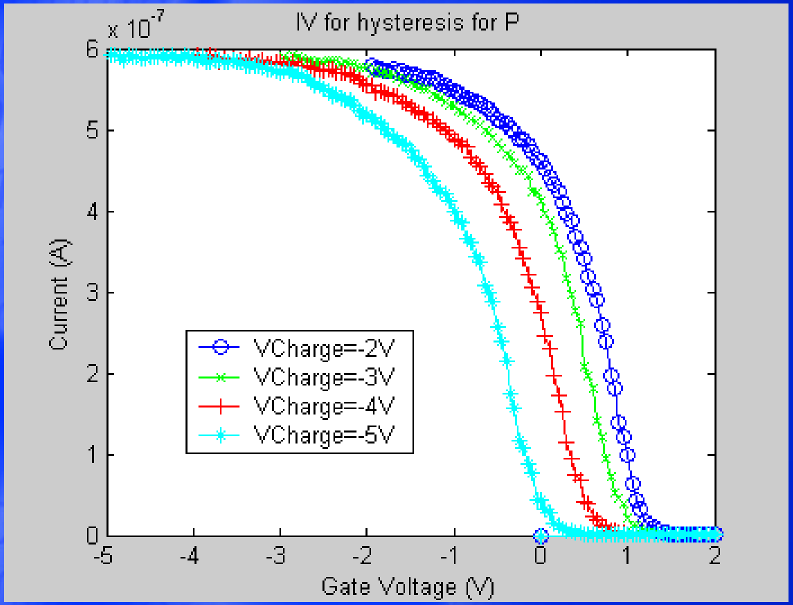
# CNT-QD Memory Device at RT

**Charging efficiency with traps:**

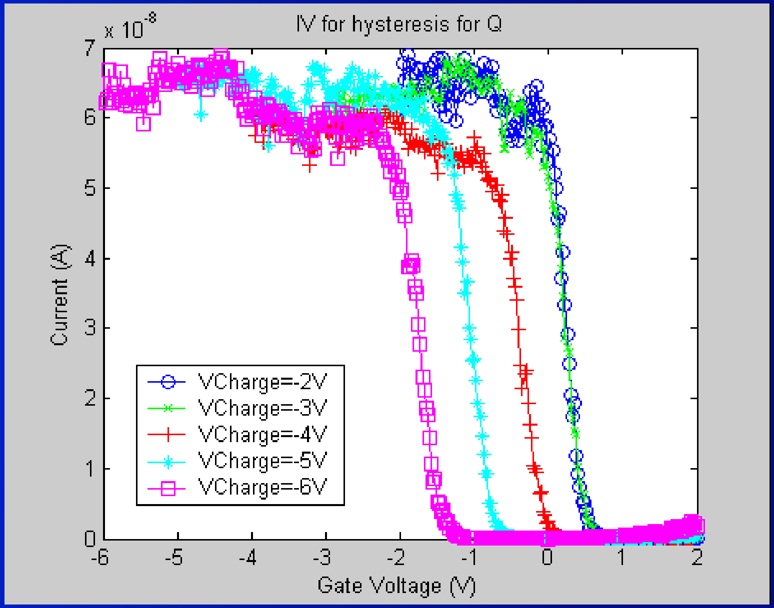
ΔVth / ΔVcharge = **1.2V/3V=0.4**




$I_D$ vs $V_G$ for device **without nanocrystals** showing charge injection into traps in the evaporated $SiO_2$

**Charging efficiency with QD:**

ΔVth / ΔVcharge = **2V / 3V=0.67**

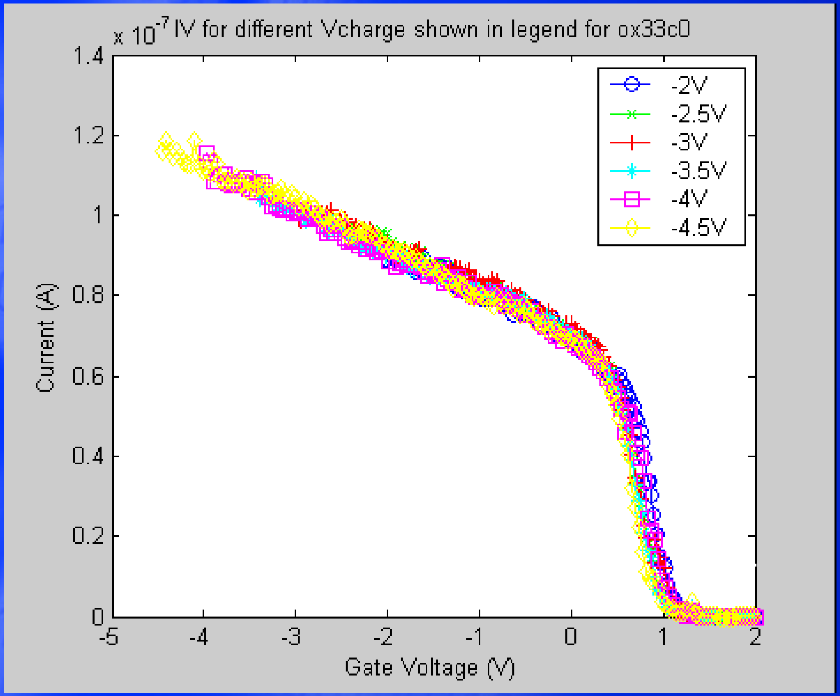



$I_D$ vs $V_G$ for device **with nanocrystals** showing charge injection into traps and nanocrystals

# CNT-QD Memory Device at Low-Temperature

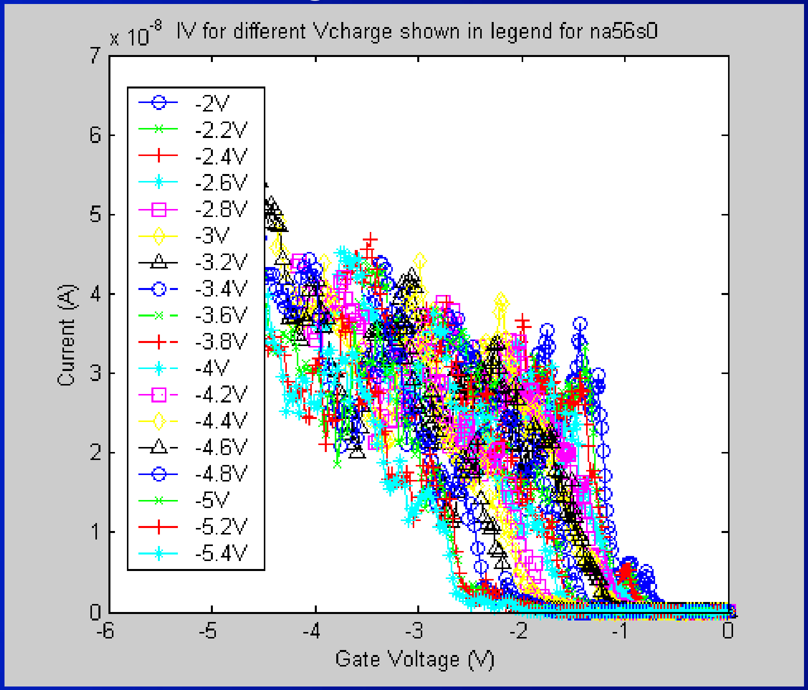
Separating trap contribution from nanocrystal charging @ T=10K

$\Delta$Vth / $\Delta$Vcharge < **0.2V / 2.5V=0.08**



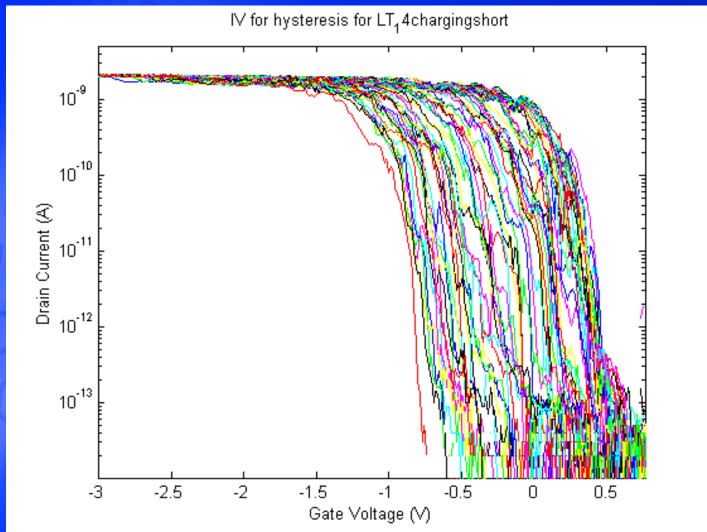

$I_D$ vs $V_G$ at T=10K for device **WITHOUT NANOCRYSTALS** showing MINIMAL charge injection

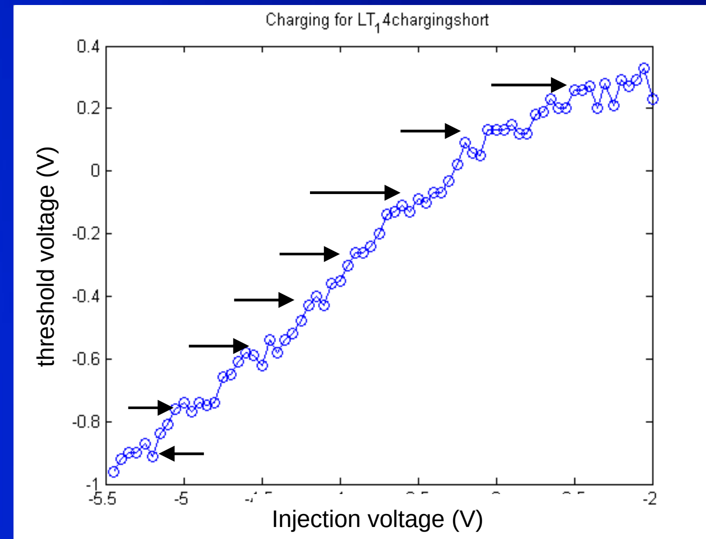
$\Delta$Vth / $\Delta$Vcharge = **1.6V / 3.4V=0.5**

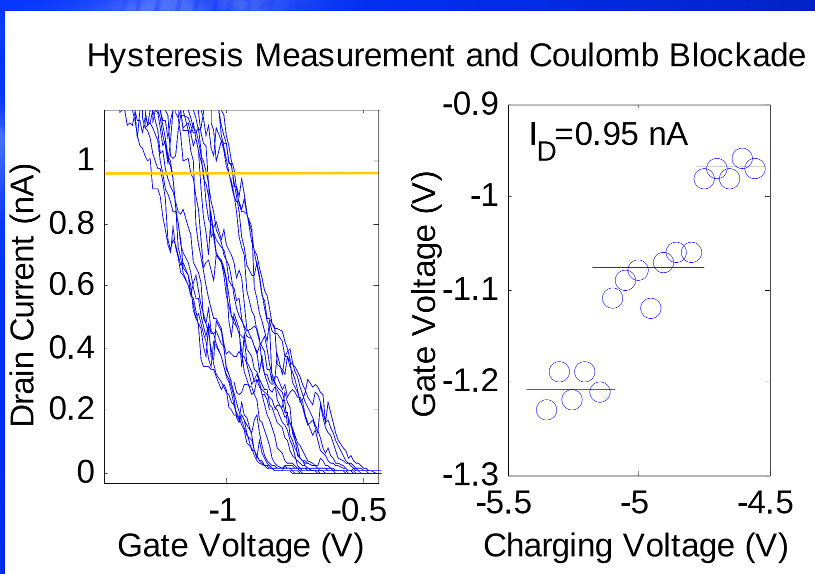



$I_D$ vs $V_G$ at T=10K for device **WITH NANOCRYSTALS** showing charge injection into NANOCRYSTALS only

# Coulomb blockade in nanocrystals: single-electron charging



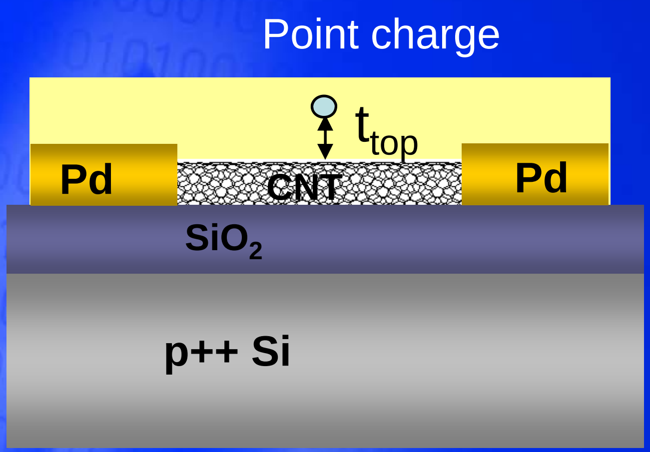



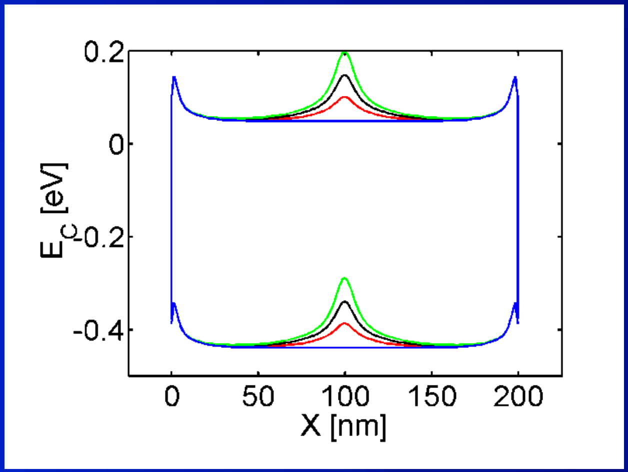

(a) Stepping the $V_{CH}$ in fine steps of 50mV shows aggregation of $I_D V_G$ curves (b) Extraction of $V_G$ for arbitrary constant $I_D$=0.95nA results in steps in $V_G$ due the combined effect of coulomb blockade in nanocrystals and single charge sensitivity of nanotube conductance.

# NEGF Simulation of CNTFET Charge Sensor

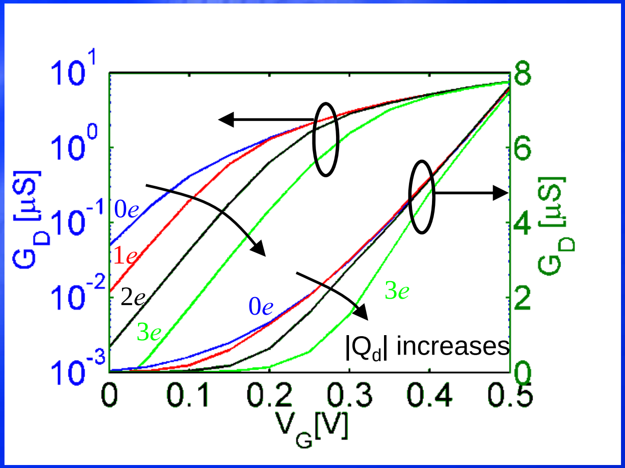
J. Guo et al., *J. Appl. Phys.* 99, 084301 (2006)

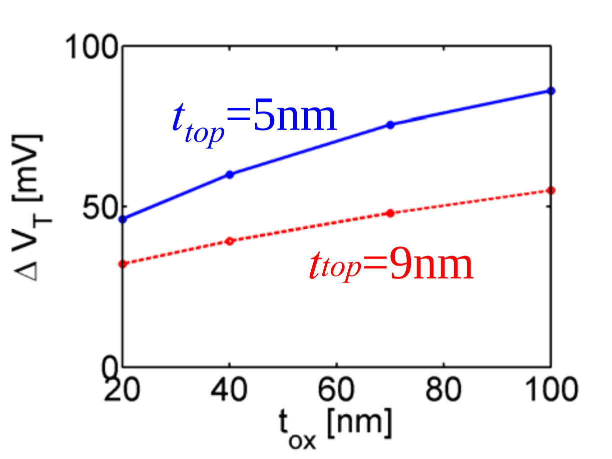


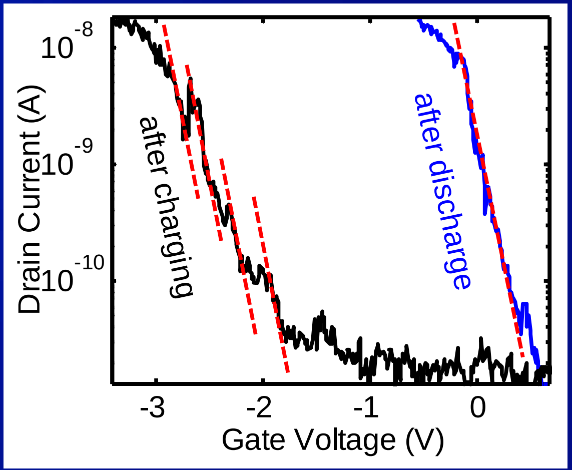

$\phi_B$=0.1eV, $d_{CNT}$~1.7nm, $L_{ch}$=200nm,
$t_{bot}$=100nm, $t_{top}$=5nm



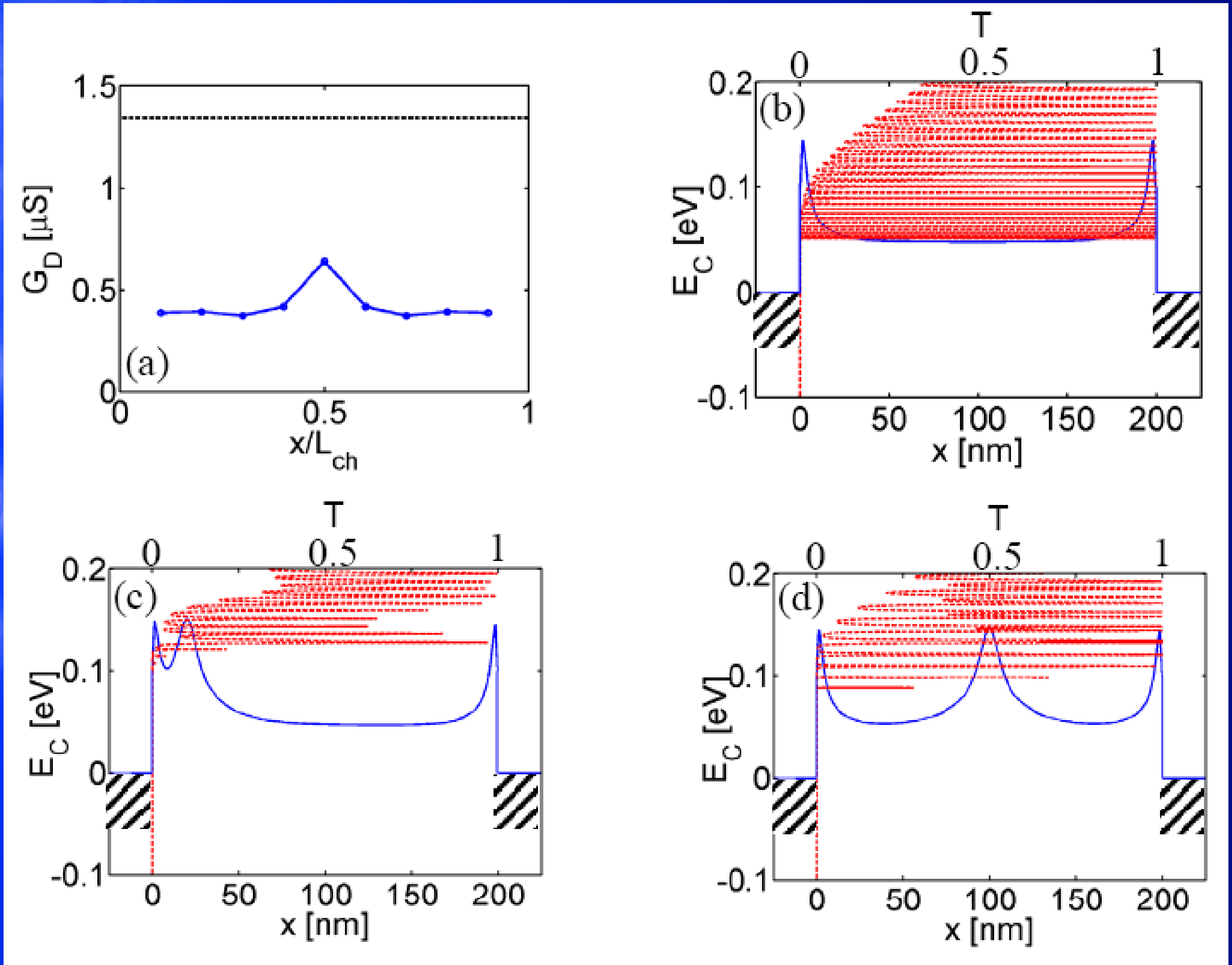

$V_D$=0V and $V_G$=0.2V



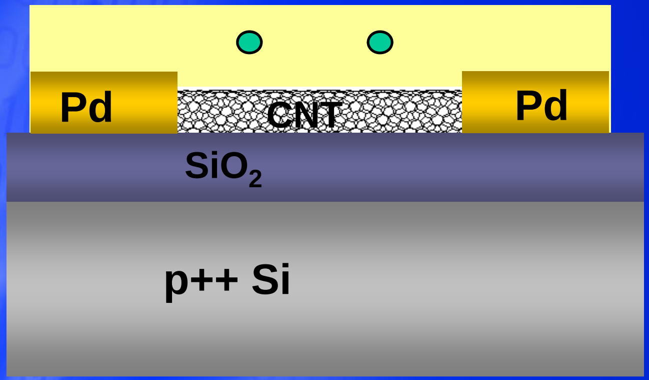



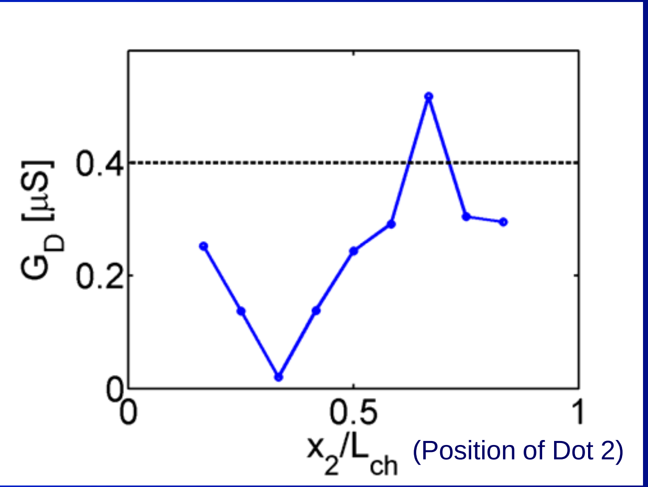
# Resonant Tunneling and Charge Position Dependence

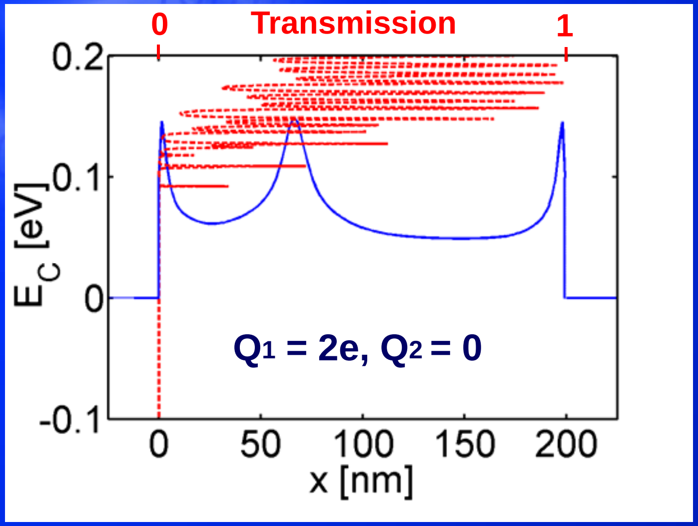


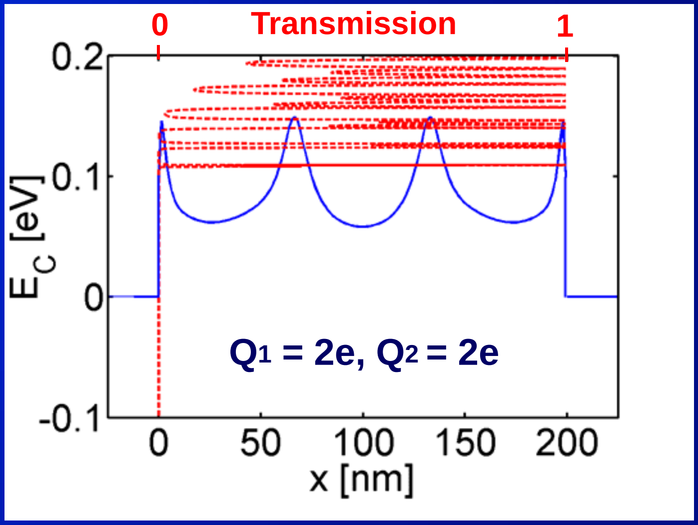
# "Bottle-neck" Effect and Resonant Tunneling




$V_D$=0V and $V_G$=0.2V



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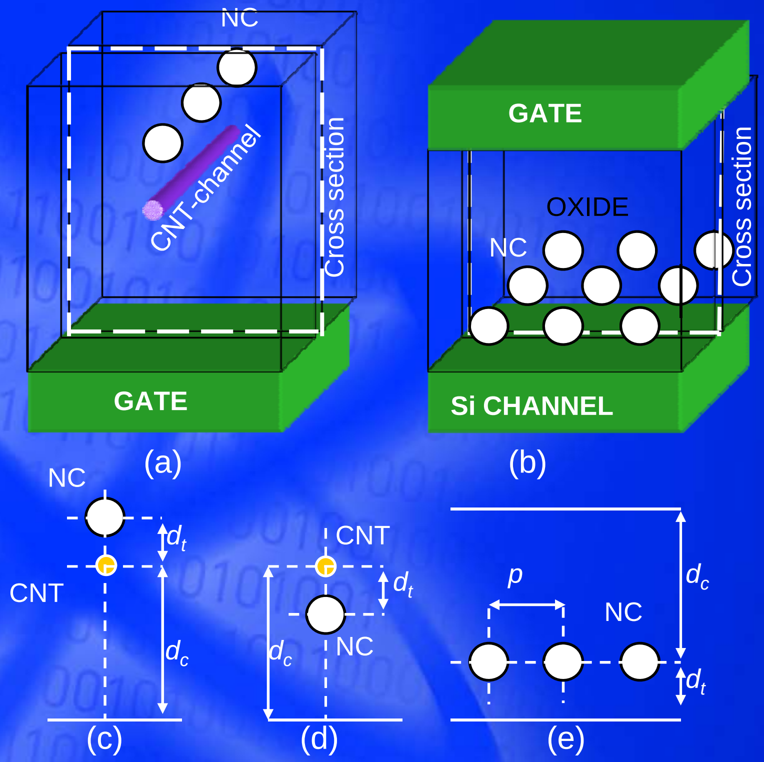
# Electrostatic Analysis

U. Ganguly et al., *Proc. SPIE*, Vol. 6003, 60030H (2005).

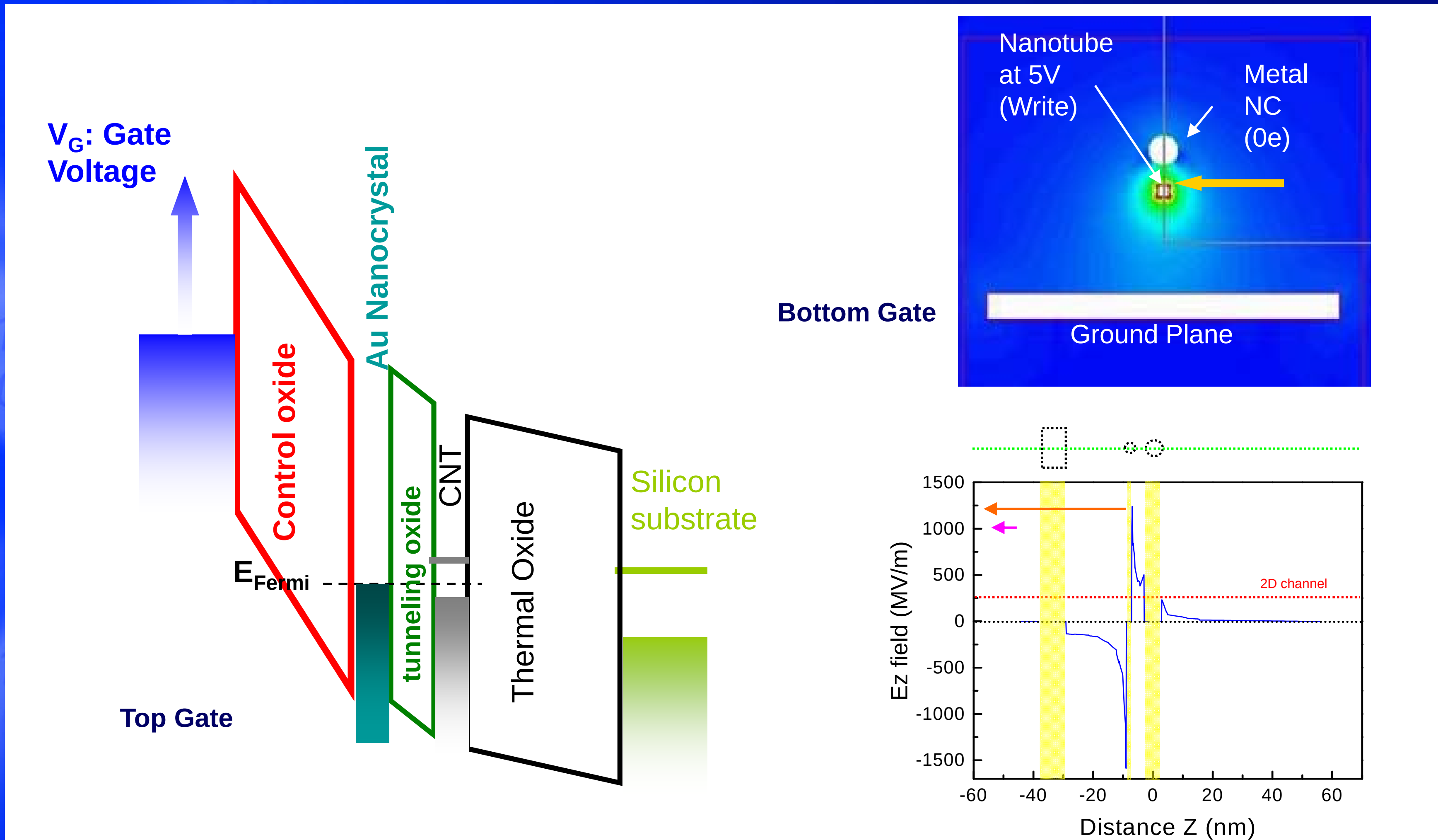



nanocrystals diameter: 6 nm; the nanotube diameter 2 nm; pitch: 12 nm; *dt* : 3 nm ( Si EEPROM) and 5 nm ( CNT-nanocrystal memory); *dc* : 30 nm (Si EEPROM); *dc* is used as a parameter to calculated capacitive-coupling of CNT nanocrystal memory structure for different *dc* : 27 nm; 30 nm ; 100 nm; .*p*: 12 nm (for all structures)

| Structural Parameters | | Potential on NC (V) | |
|---|---|---|---|
| | $d_c$ (nm) | Capacitive Coupling $V_G$=5 (Programming) | Self Capacitance $q_{NC}$=5e (Retention) |
| 1NC-CNT BG | 27 | 2.52 | -0.517 |
| | 30 | 2.35 | -0.519 |
| | 100 | 1.77 | -0.528 |
| 1NC-CNT TG | 30 | 2.69 | -0.509 |
| 3NC-CNT BG | 30 | 2.33 | -0.68 |
| 1 NC-Si | | 0.81 | -0.46 |
| 3 3 NC -Si | | 0.74 | -0.67 |

Enhancement of electric field asymmetry in the CNT-NC- memory **makes it easy to be programmed while keeping similar retention capability** compared to the NC planar memory**.**

# Energy Band Diagram - Charging Mechanism




Note: For 1D channel, the fringe field makes the electrostatic potential profile of the back gate geometry the same as top-gate geometry shown here.



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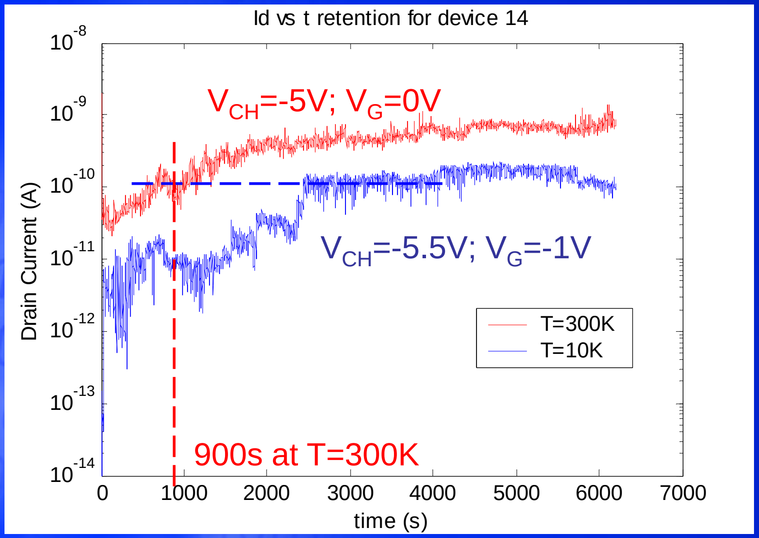
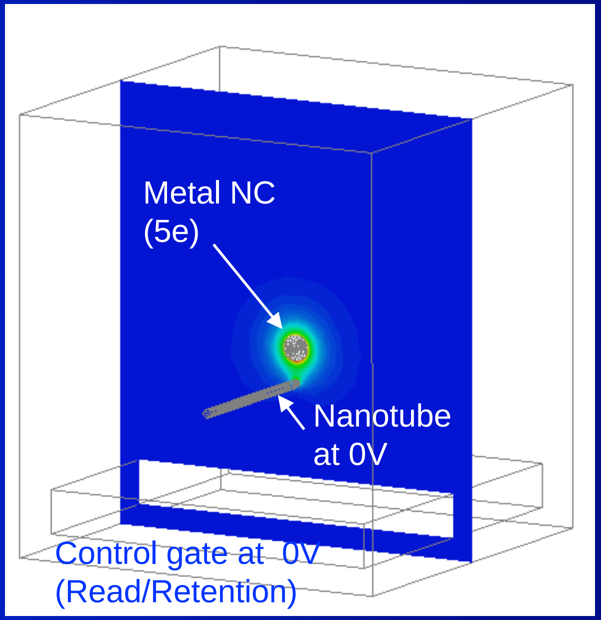
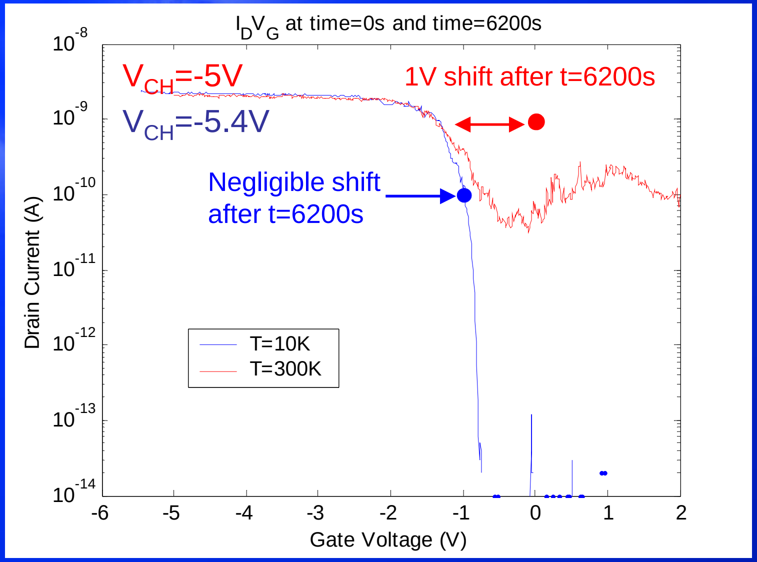
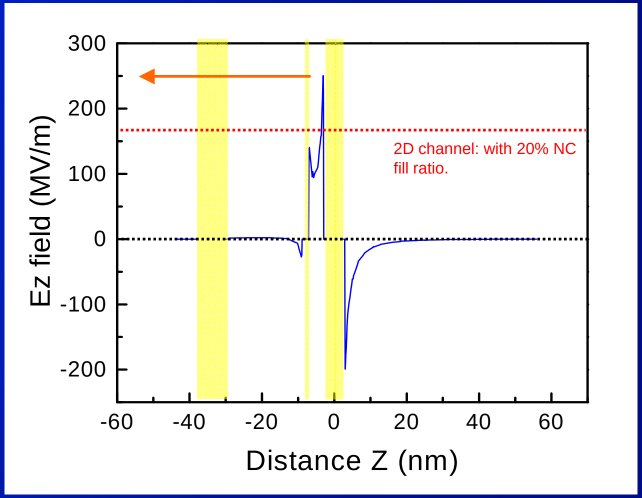
# Retention Measurements



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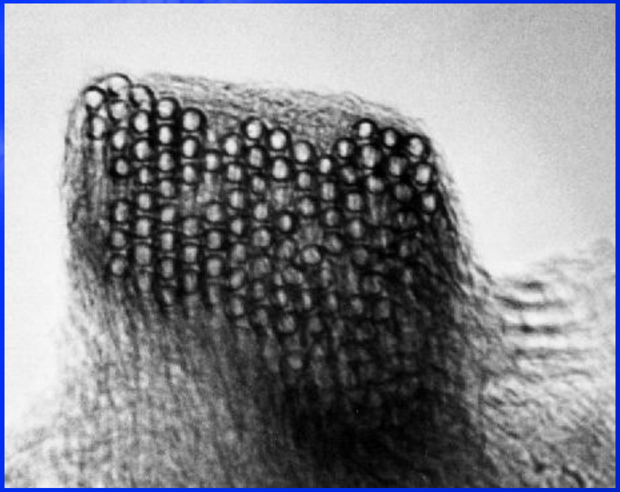
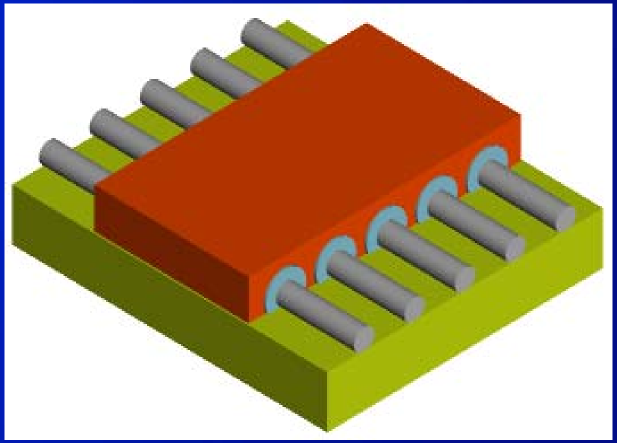
# Major Challenges for HVM of CNT Devices

- ✓ **Electronically pure material: precise property control**
  - Pure metallic nanotubes for on-chip interconnection.
  - Pure semiconducting nanotubes with a well-defined energy-gap for high performance transistors and memory devices.
- ✓ **Patterning technology: precise registry and orientation control**
  - Array with regular spacing.
  - Connection to electrodes.





SWNT tri-gate transistor



Yuegang Zhang

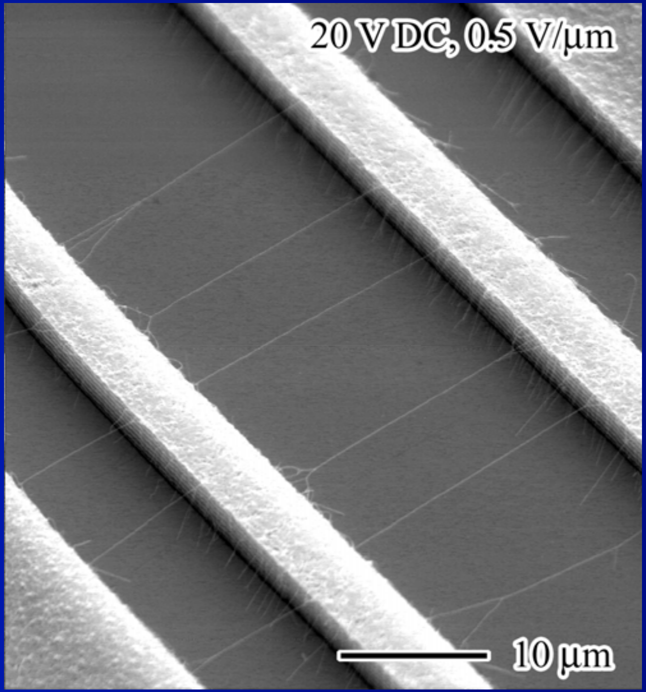
# What in-growth control can do and cannot do…

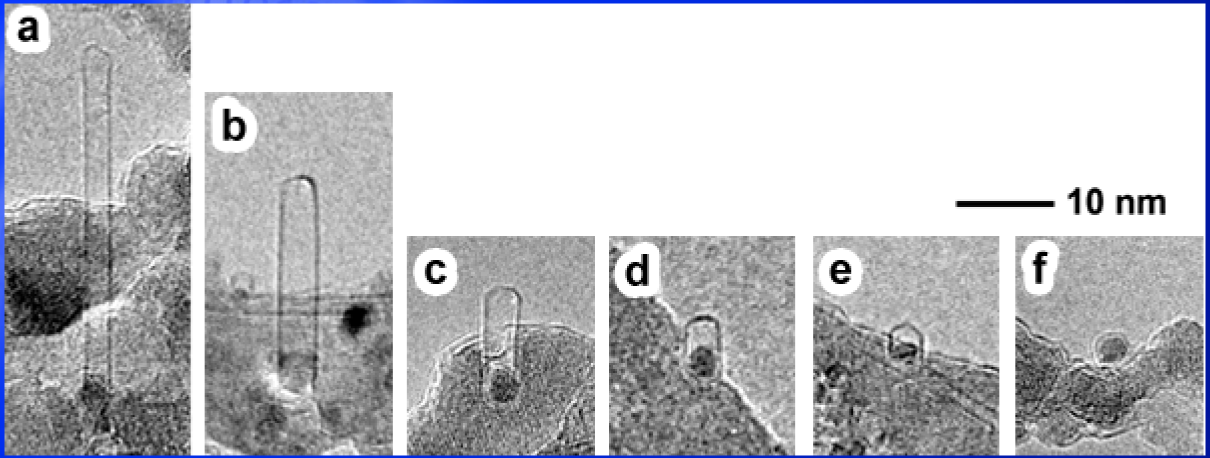
**Controlling diameter and orientation in CVD process…**

- Tube diameter dependence on the size of catalyst nanoparticles
- Electrical-field-directed growth

**However…**

- The diameter difference of a metallic and a semiconducting nanotube can be as small as merely 0.03 angstroms.
- There is no method available (yet) to control the chirality by controlling catalyst.




- There is no reliable way to control tube-tube spacing (yet).



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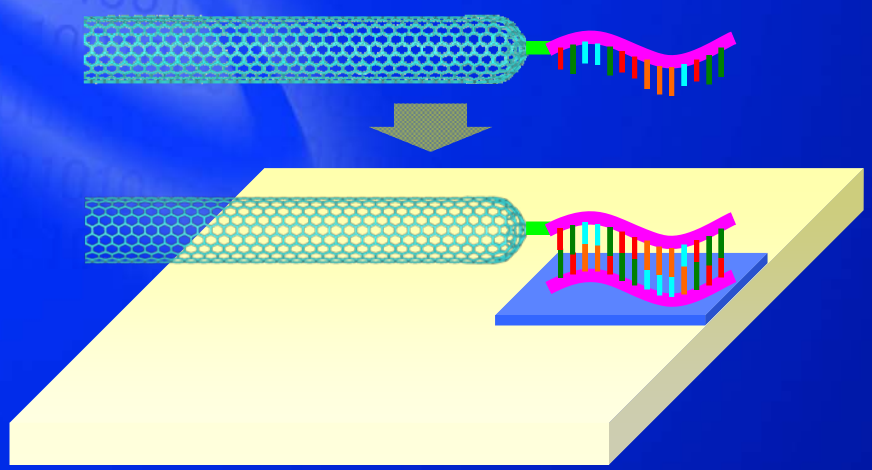
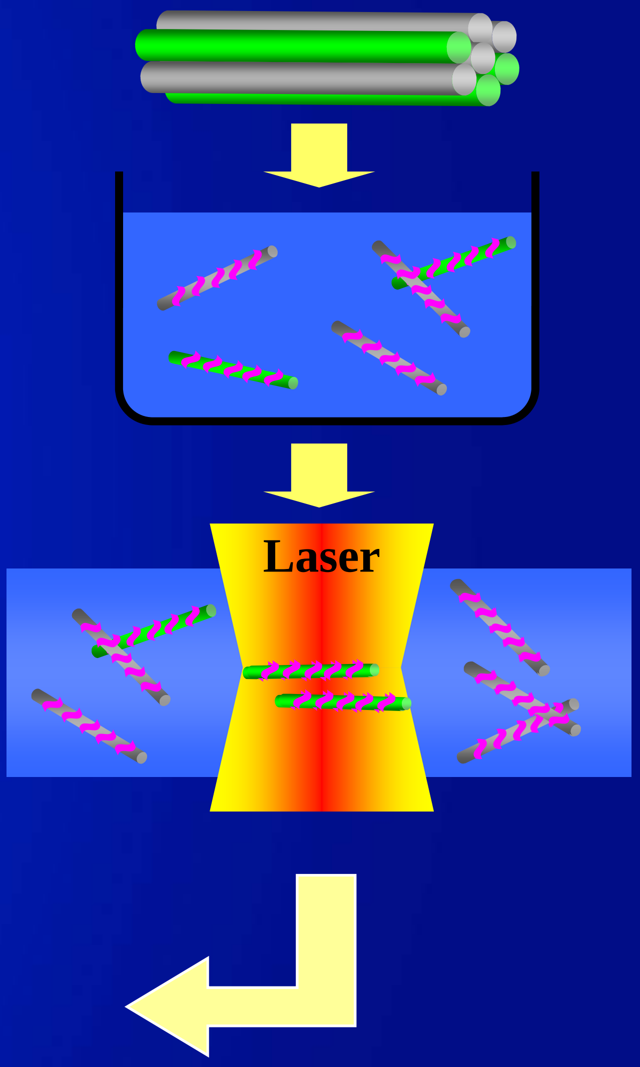
# Alternative Approach: Post-growth Processing

- **Nanotube functionalization**
  - To isolate individual tubes from mixed bundle
- **Sorting**
  - Separate nanotube types & sizes
- **Assembly into functional array**
  - Directed self-assembly





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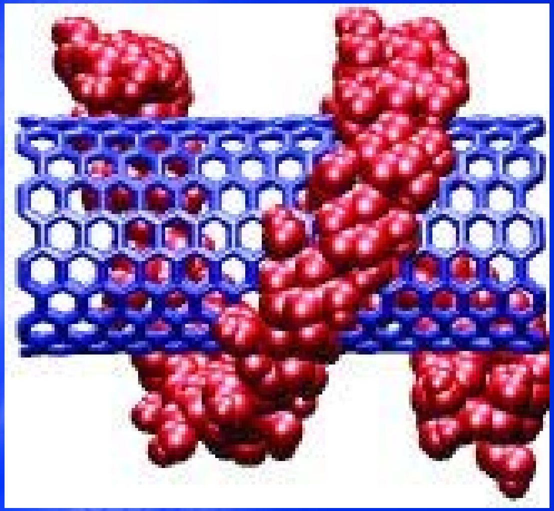
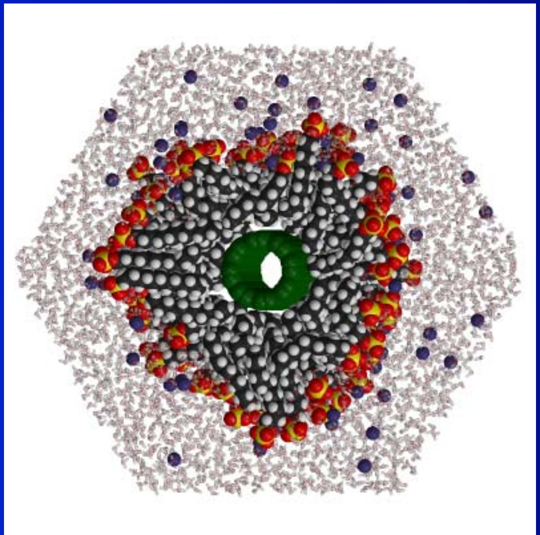
# Solubilization of SWNT

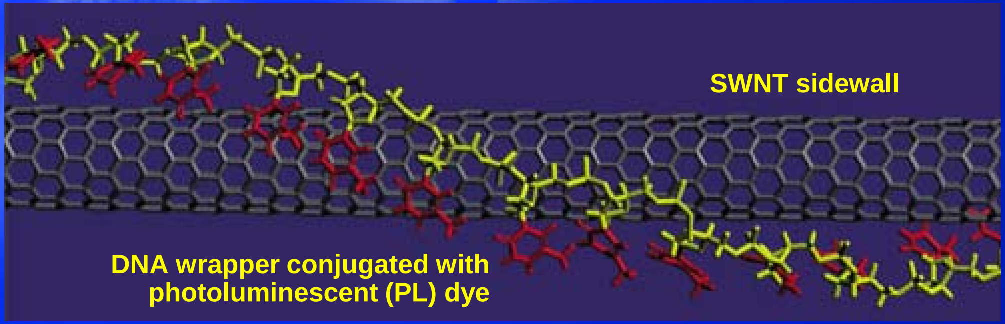
**(Prior-arts)**



polymer wrapping

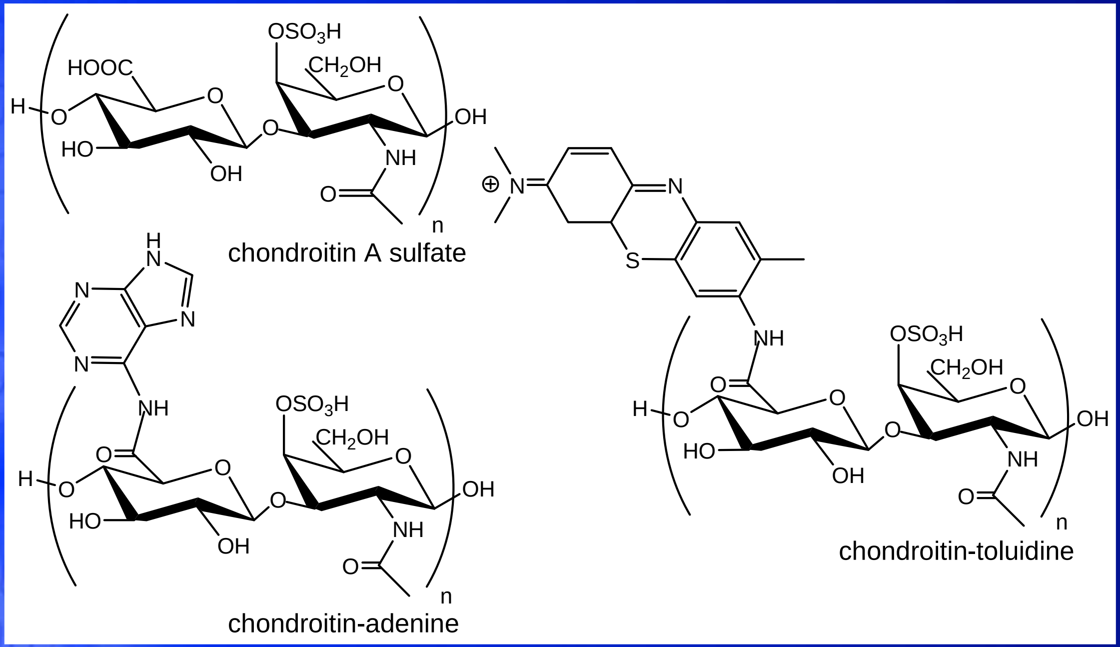


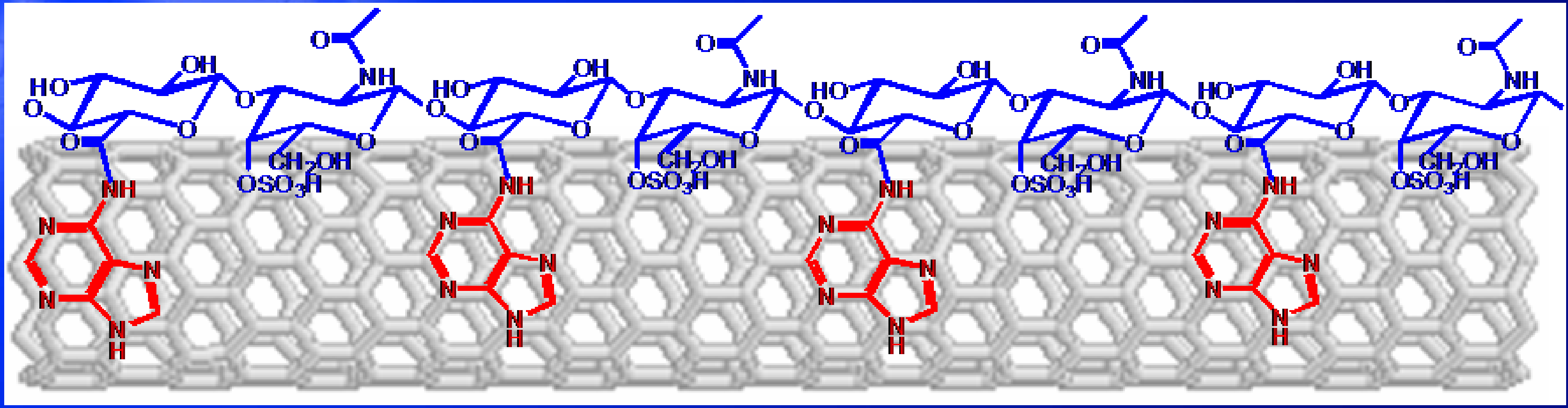
micellular suspension




**To overcome their poor intrinsic solubility, SWNTs are ultrasonically dispersed as individuals and wrapped with water-soluble surfactants or polymers to make them compatible with microfluidics and self-assembly reactions.**

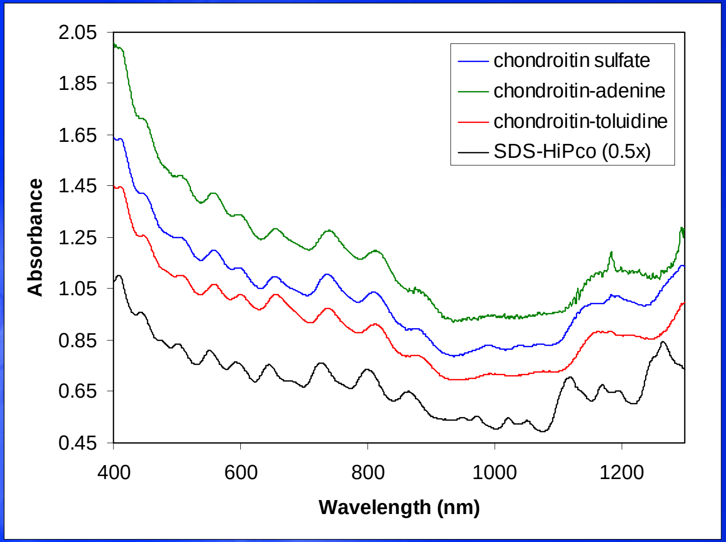
# Chondroitin derivatives for selective solubilization

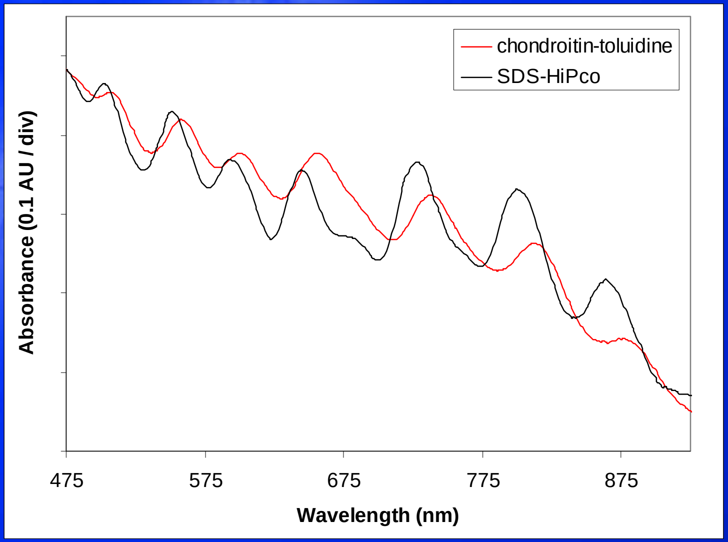


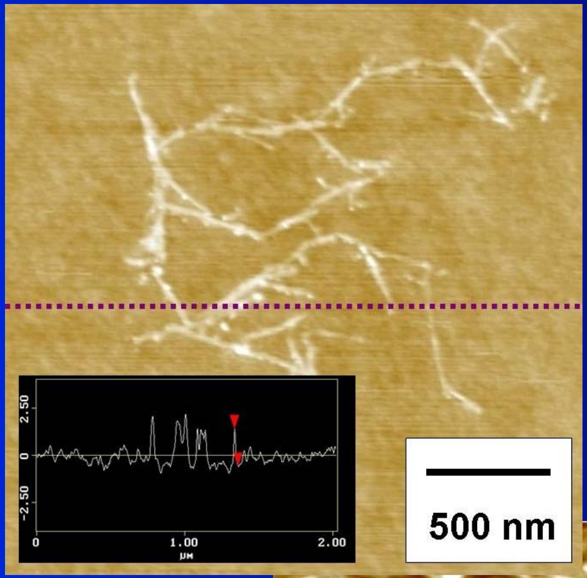
R. Chen et al., to be submitted

# Chondroitin derivatives for selective solubilization

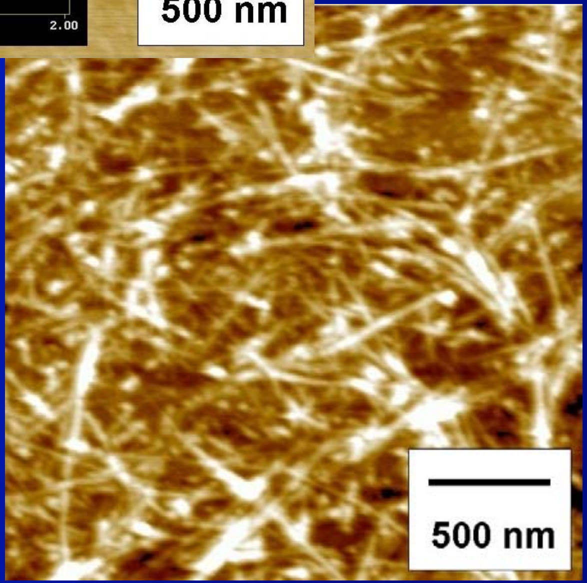



UV-vis-NIR



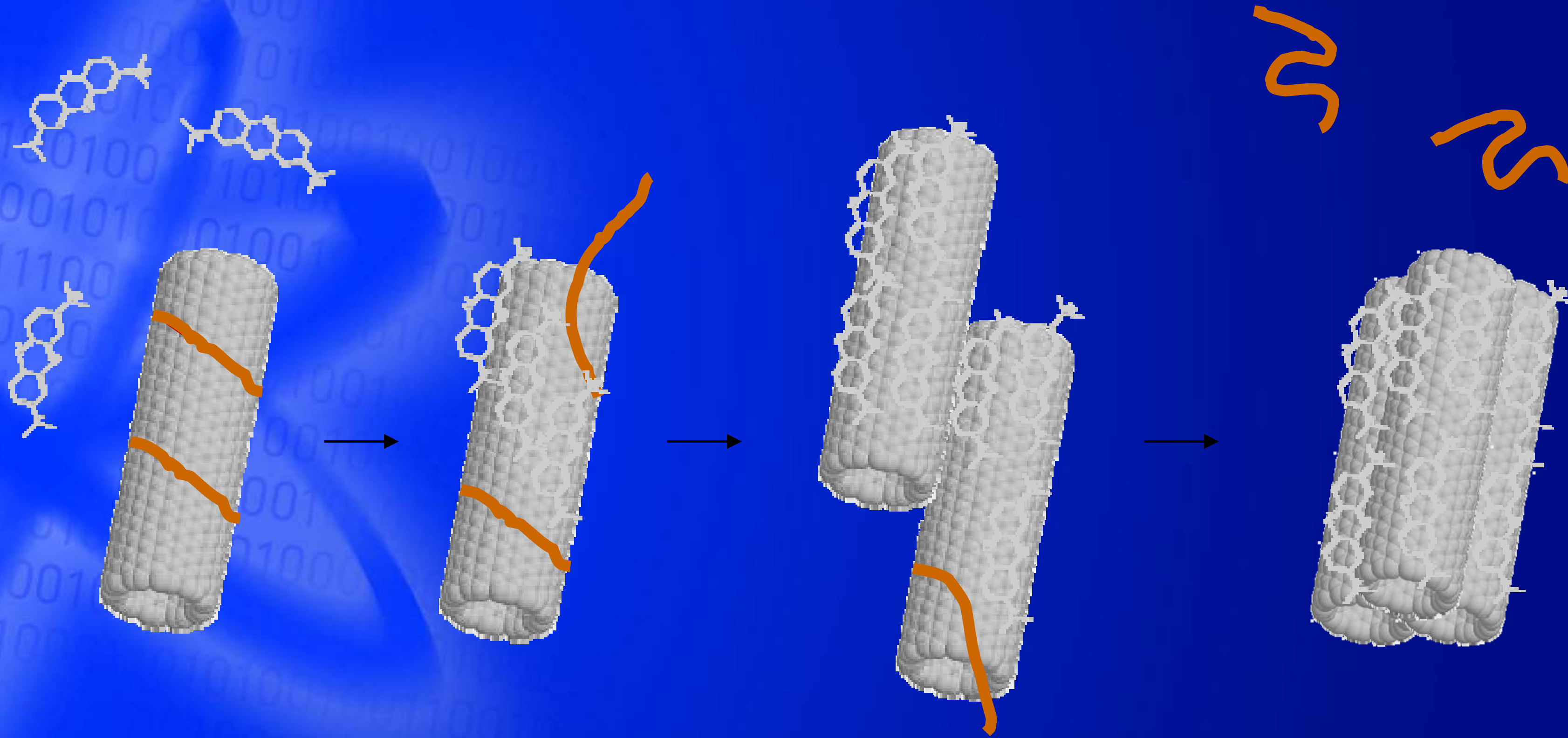

AFM:
Chondroitin-Adenine SWNT




R. Chen et al., to be submitted

# De-functionalization with small molecules

**R. J. Chen and Y. Zhang, *J. Phys. Chem.* B 110, 54 (2006)**



Poly $T_{30}$-coated CNTs

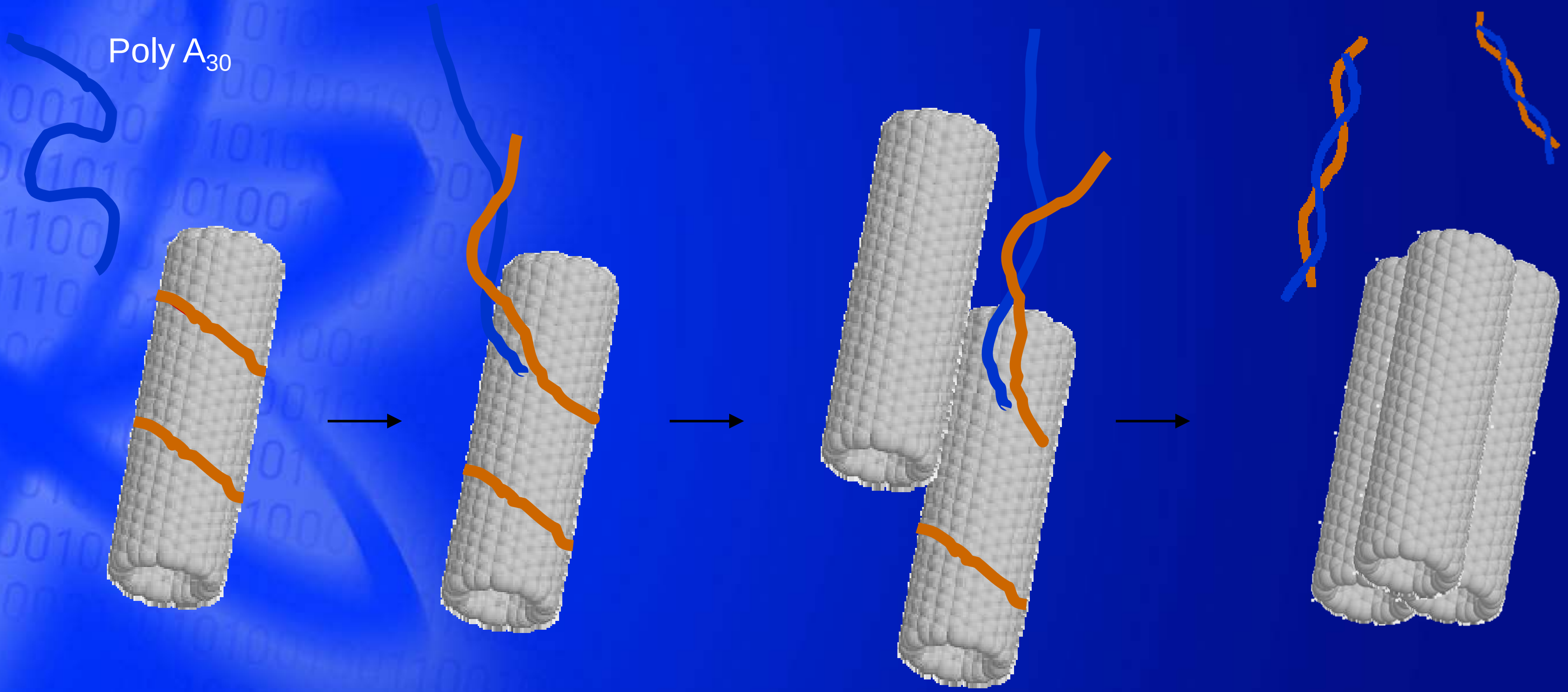
Molecule replacement initiates DNA desorption

CNTs begin to re-bundle

Desolubilized CNTs precipitate out

# De-functionalization using complementary ss-DNA

**R. J. Chen and Y. Zhang, *J. Phys. Chem.* B 110, 54 (2006)**



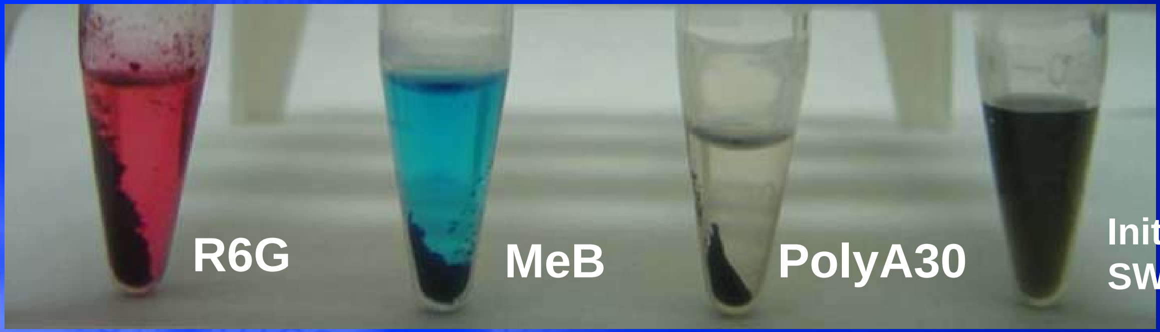

Poly $T_{30}$-coated CNTs

Hybridization initiates DNA desorption

CNTs begin to re-bundle

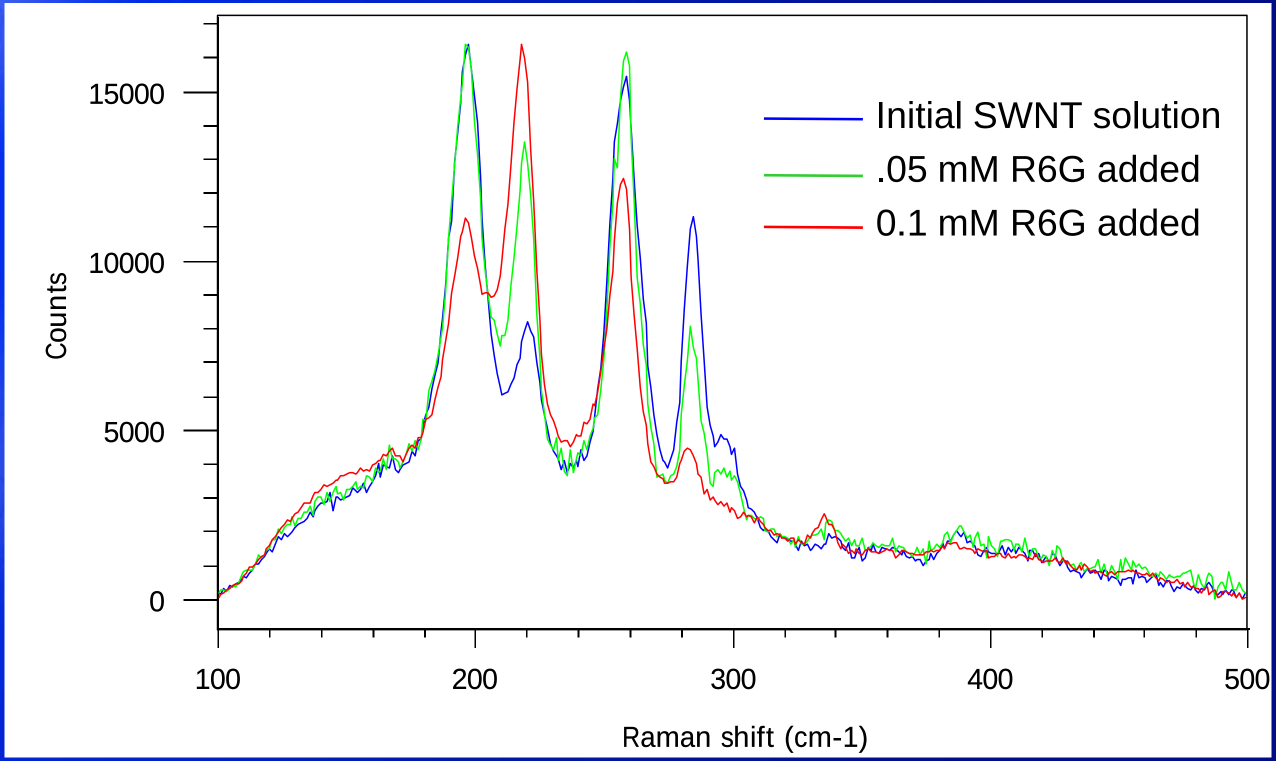
Desolubilized CNTs precipitate out

# De-functionalization: Selective Precipitation?



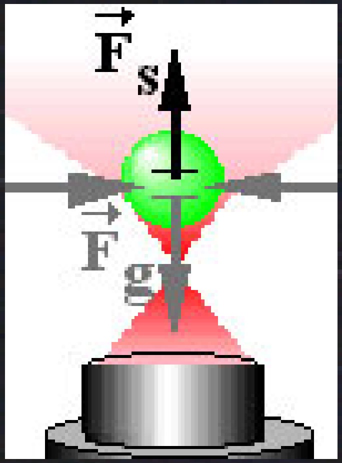

Initial DNA-solubilized SWNT solution

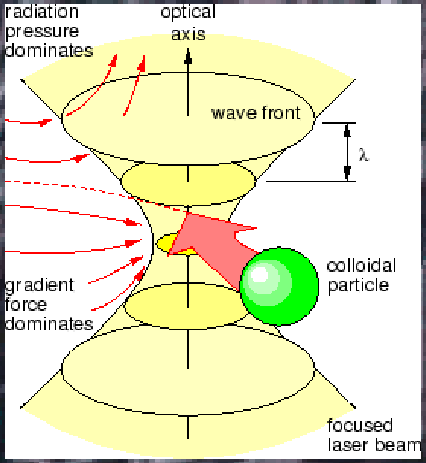
R. J. Chen and Y. Zhang,
*J. Phys. Chem.* B 110, 54 (2006)




633 nm Excitation

# Optical Trapping: a new method for nanotube sorting




- Laser dipole trap is based on the interaction of electrical field with instantaneous dipole momentum induced in molecules (neutral particles).
- Trapping: Laser frequency < resonant frequency.
- By tuning the laser frequency, M- or S-tubes can be selectively trapped or released.
- Nanotubes can be sorted according to their band-gaps (diameters).

# The Physics behind Optical Trapping of Carbon Nanotubes

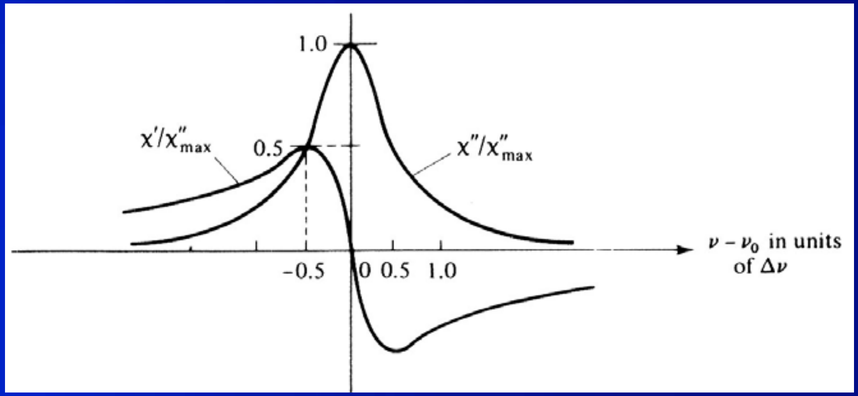
Induced dipole momentum of a neutral particle in E-field

$P = \varepsilon_0 \chi E$

Energy (isotropic medium)

$U = - \langle P \cdot E \rangle = - \varepsilon_0 \chi \langle E \rangle^2$

$\chi(\omega) = \chi'(\omega) + i\, \chi''(\omega)$




When $\omega < \omega_0$, $\chi'(\omega) > 0$,

$\therefore$ E↑ ⇒ U↓

The particle moves towards the center of a laser beam (assuming a Gaussian intensity distribution).

**What is special for 1-D object?**

- Dipole always parallel to the axis

$P = P_{\parallel} + P_{\perp} \cong P_{\parallel} = \varepsilon_0 \chi E_{\parallel}$

$U = - \langle P \cdot E \rangle = - \varepsilon_0 \chi \langle E \rangle^2 \cos \theta$

$\therefore$ E↑ ⇒ U↓ & θ↓ ⇒ U↓

Trapping & Alignment



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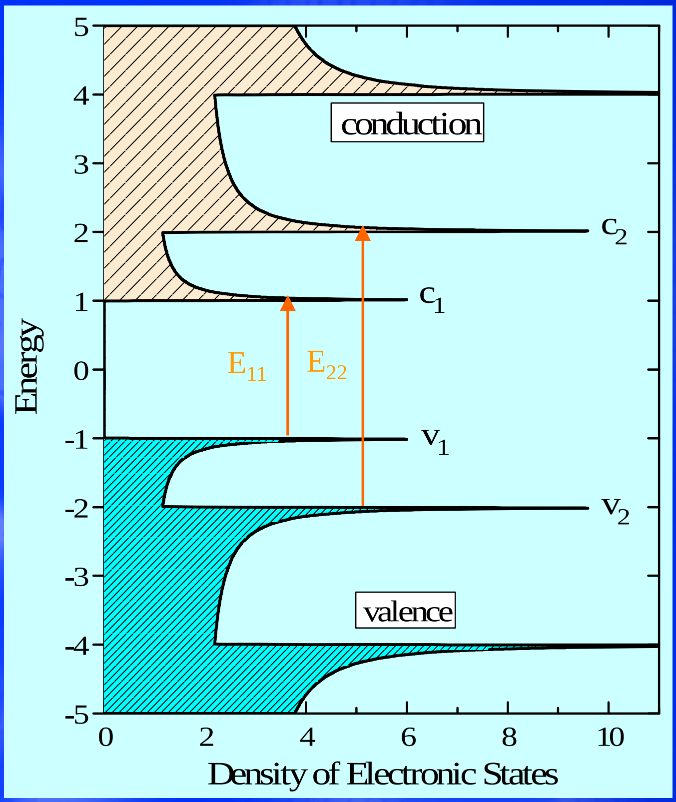
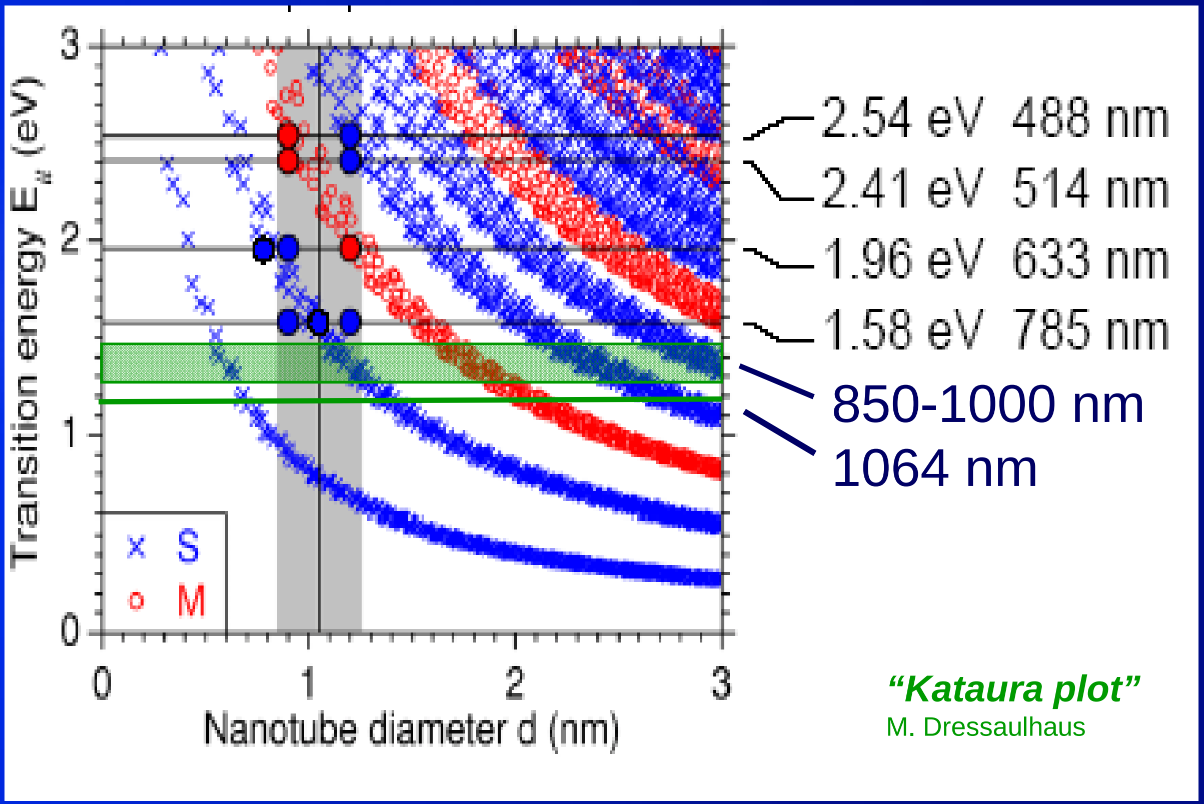
# Selectivity of Optical Trapping of Carbon Nanotubes

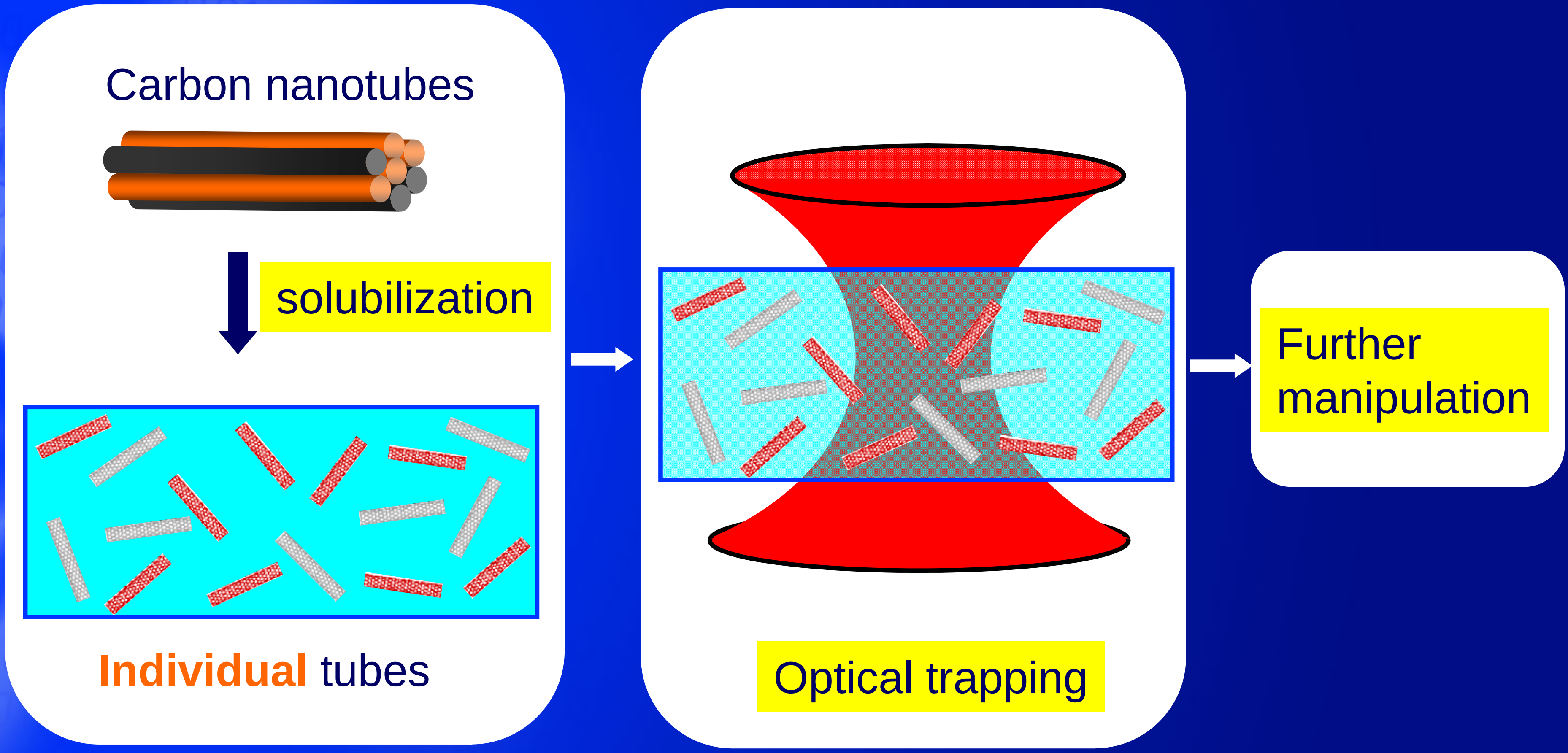



*"Kataura plot"*
M. Dressaulhaus

**The interband transition energies $E_{ii}$ (therefore, the optical resonance frequencies $\omega_0^{ii}$) are uniquely determined by the diameter and chirality**

# If the sample is properly prepared…
# If a trapping laser is properly chosen…





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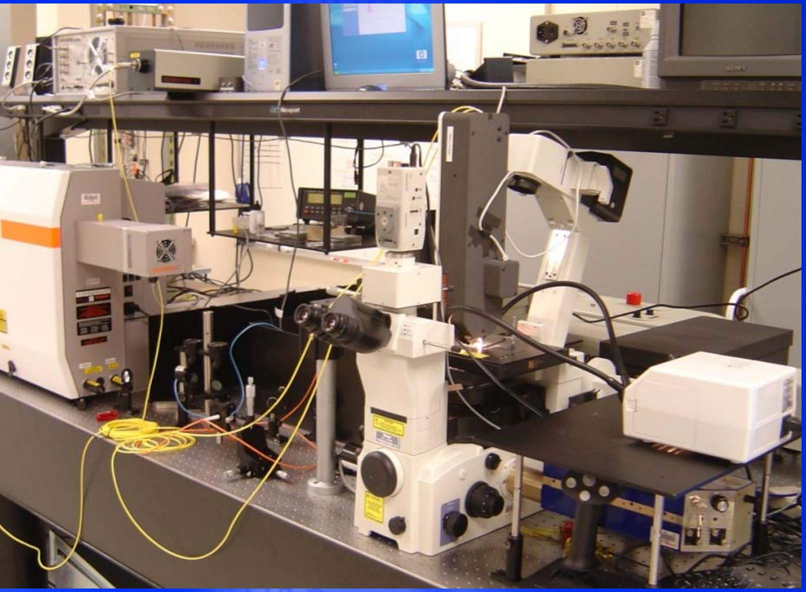
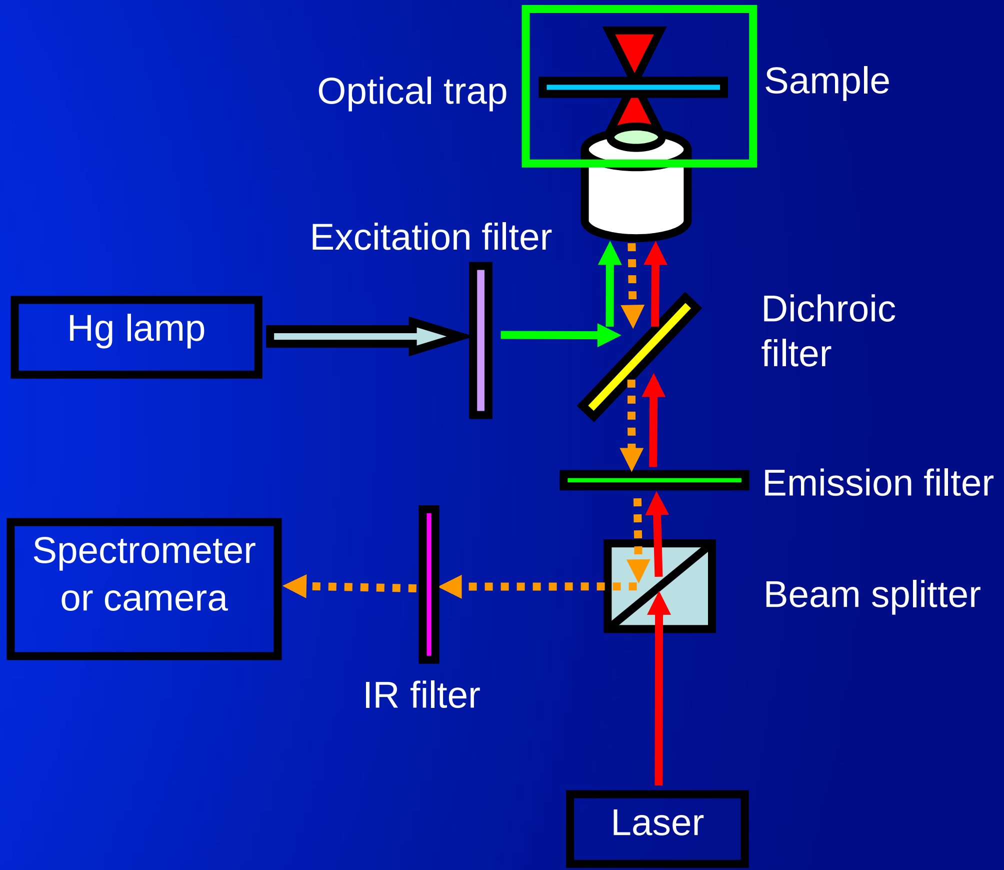
# Experimental Setup

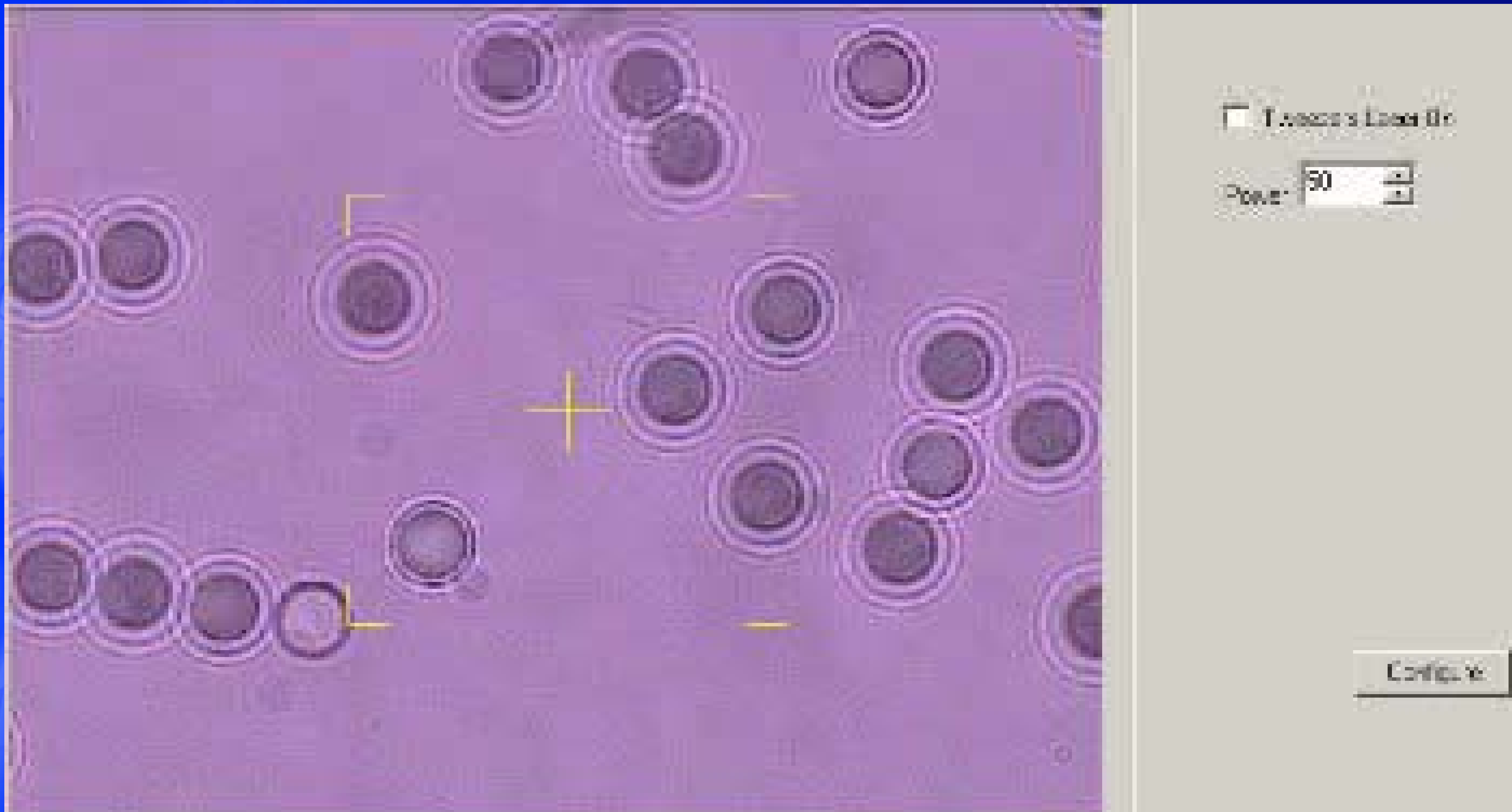





**Nano Lett. 4, 1415 (2004)**

**Lasers:** *Nd:$YVO_4$ 1064 nm*
*Ti:Sapphire 720-1000 nm*
*Millennia 532 nm*

# Video of optical trapping of polystyrene beads



Laser power: 100 mW.
Laser wavelength: 1064 nm.
Beads: polystyrene, 4 um in diameter.



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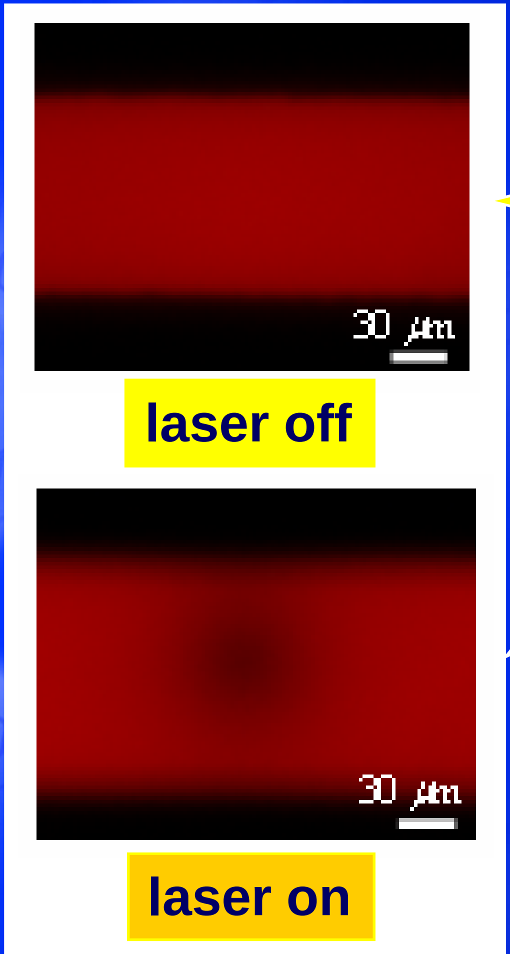
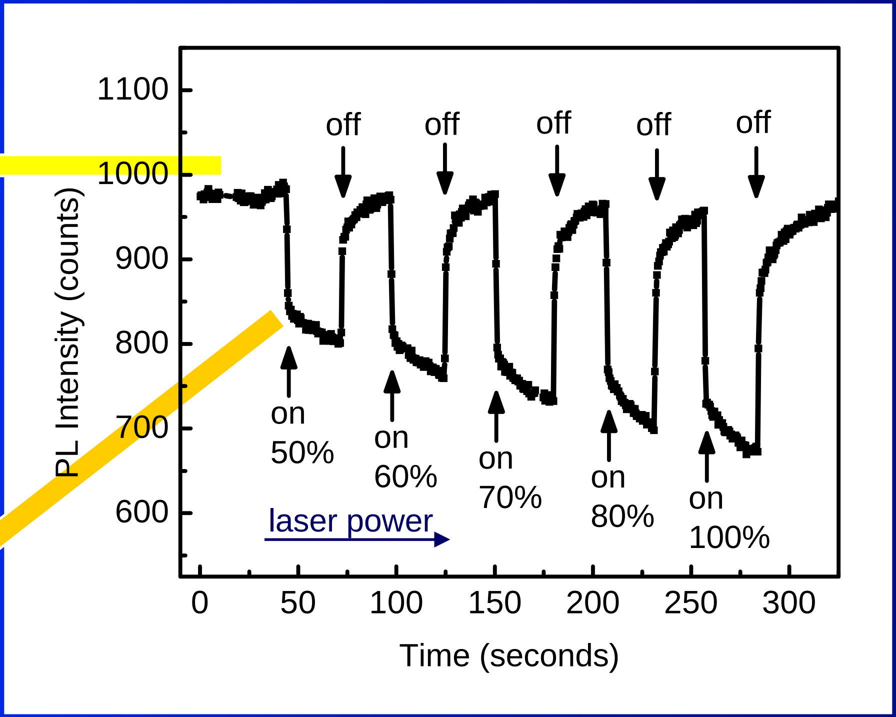
# Visualizing Nanotube Trapping: "Dark Cloud"




*Laser: 1064 nm; 150 mW (max.)*

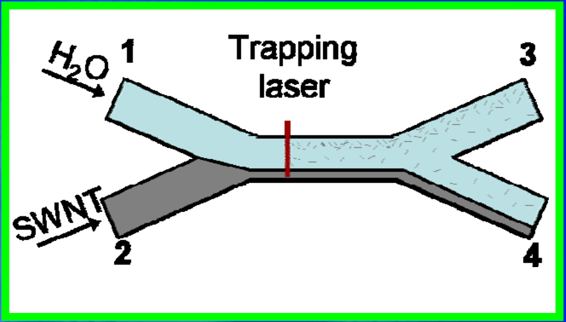
Samples:

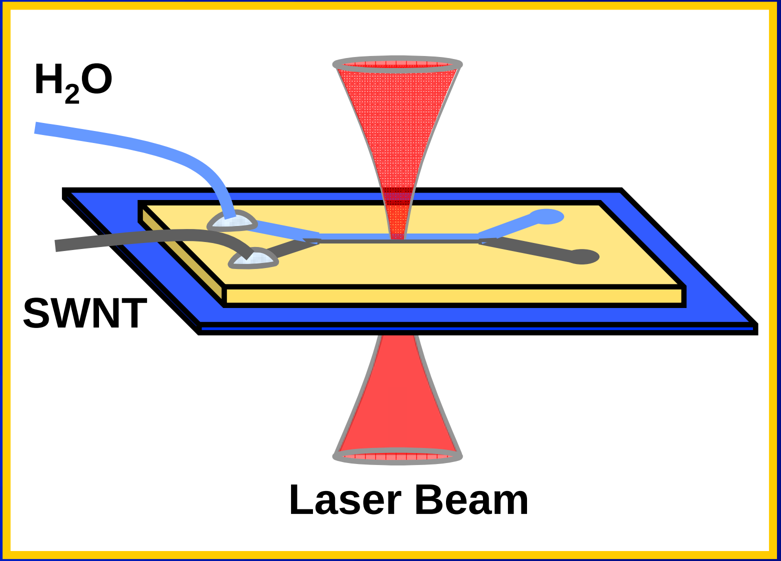
- DNA-CNT and DNA-TAMRA mixture.
- DNA-TAMRA concentration (0.003 µM).
- SWNT concentration 0.083 mg/mL,

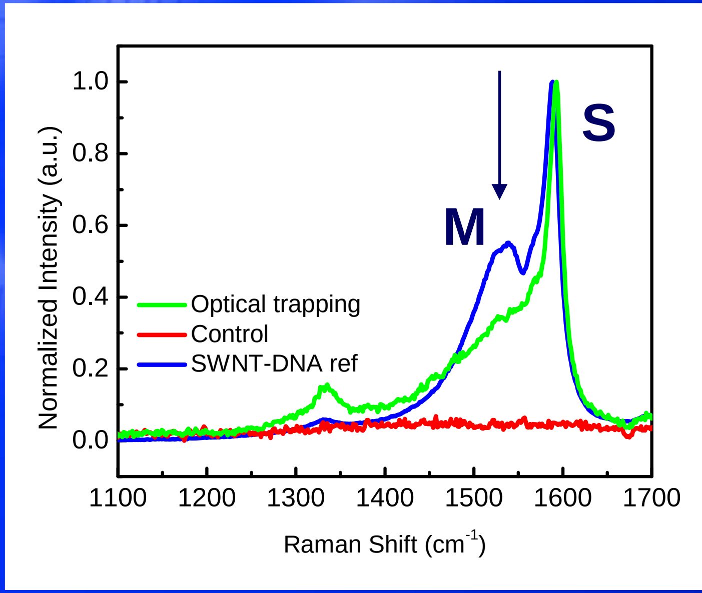
# CNT trapping video


Laser power: 300 mW
Laser wavelength: 1064 nm
CNT-DNA-TAMRA mixture

# Optical Sorting in Microfluidic Device

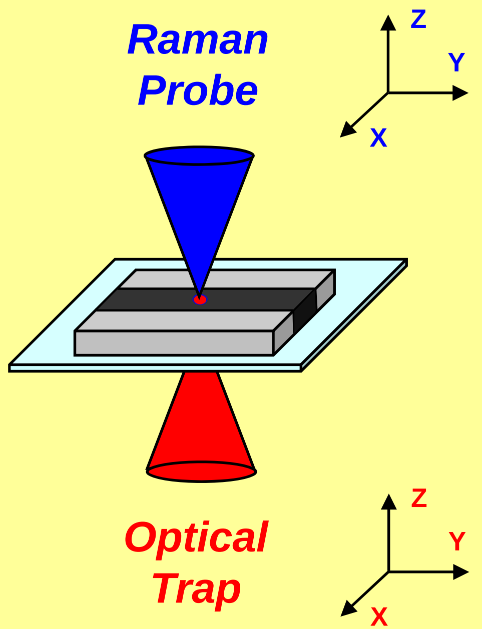


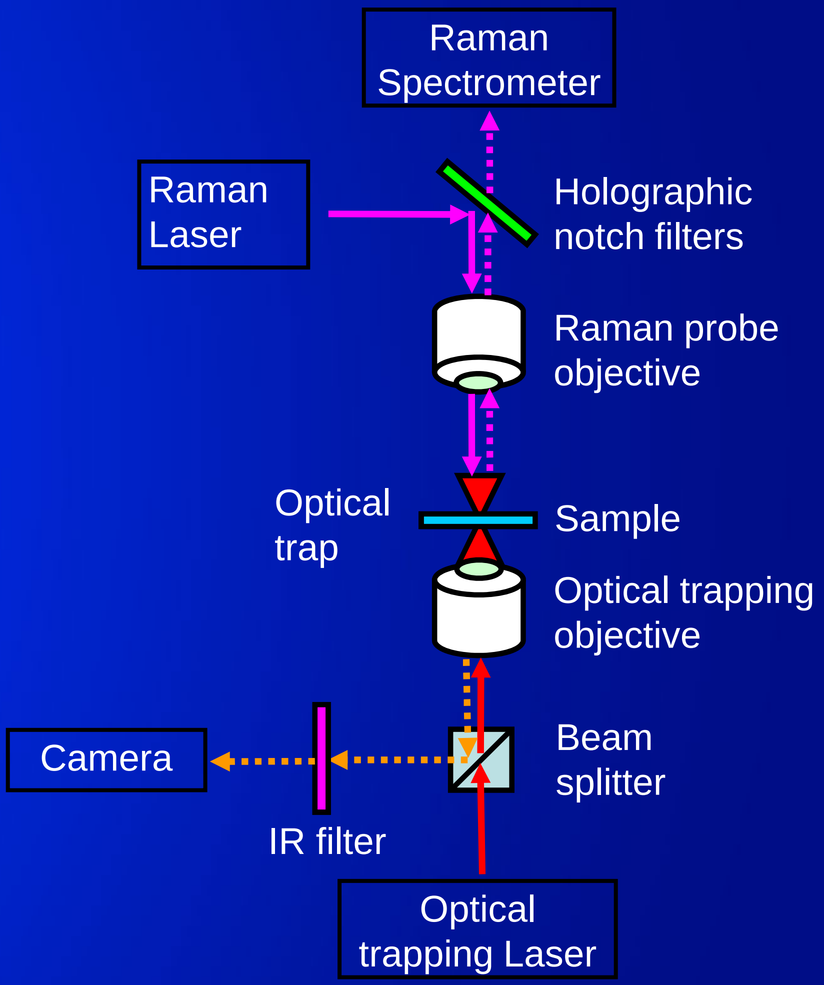




Laser sweeps across the channel to trap CNTs and release them into the water side

# *In-situ* Raman / Optical Trapping



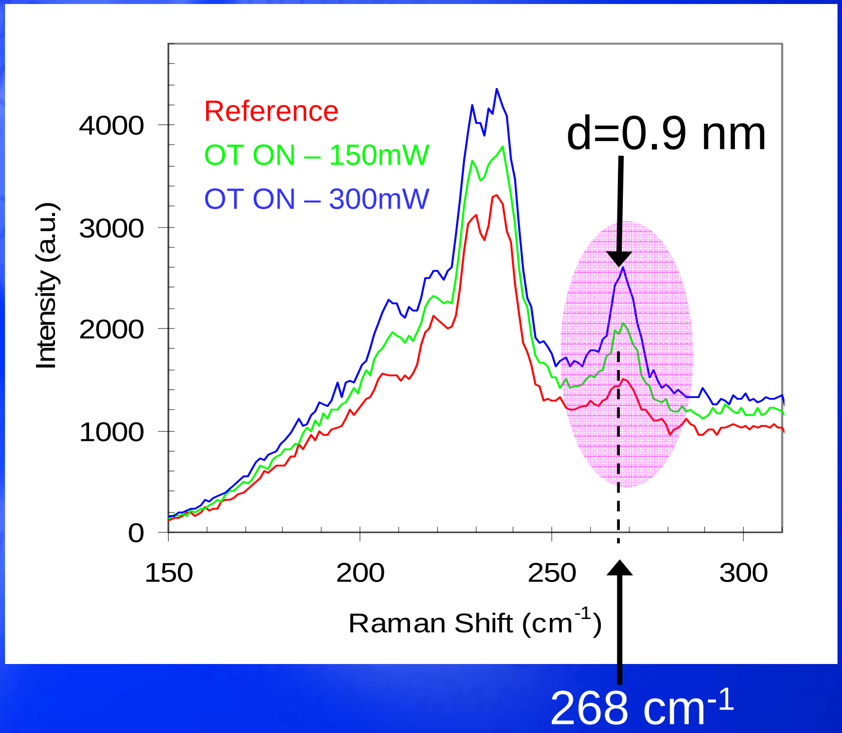

***- Dual Beam -***
***O.T. & Raman Spectroscopy***

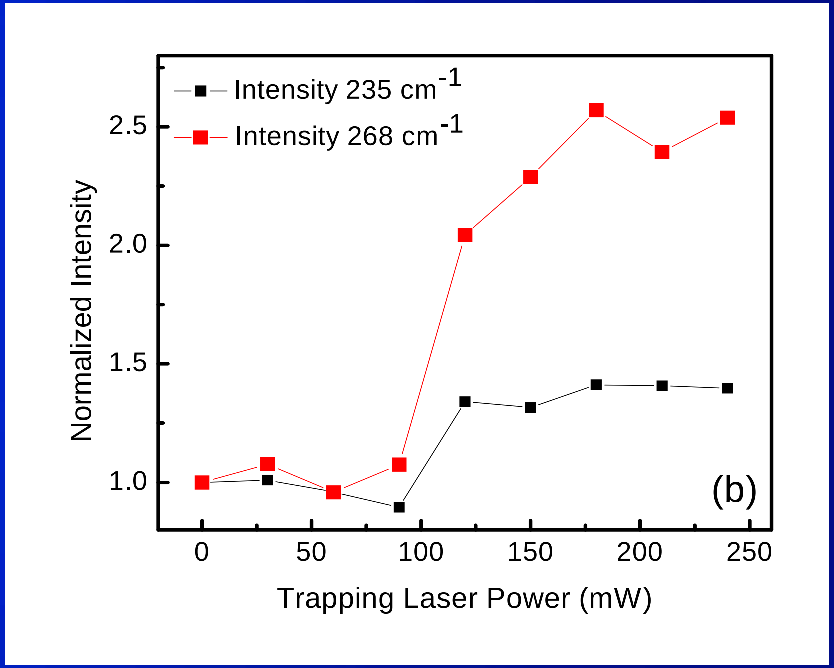



***Proceedings of SPIE*, Vol 5593, pp. 73-81, 2004**

# *In-situ* Raman / Optical Trapping

**DNA-HiPco: *1064 nm trapping, 785 nm probing***

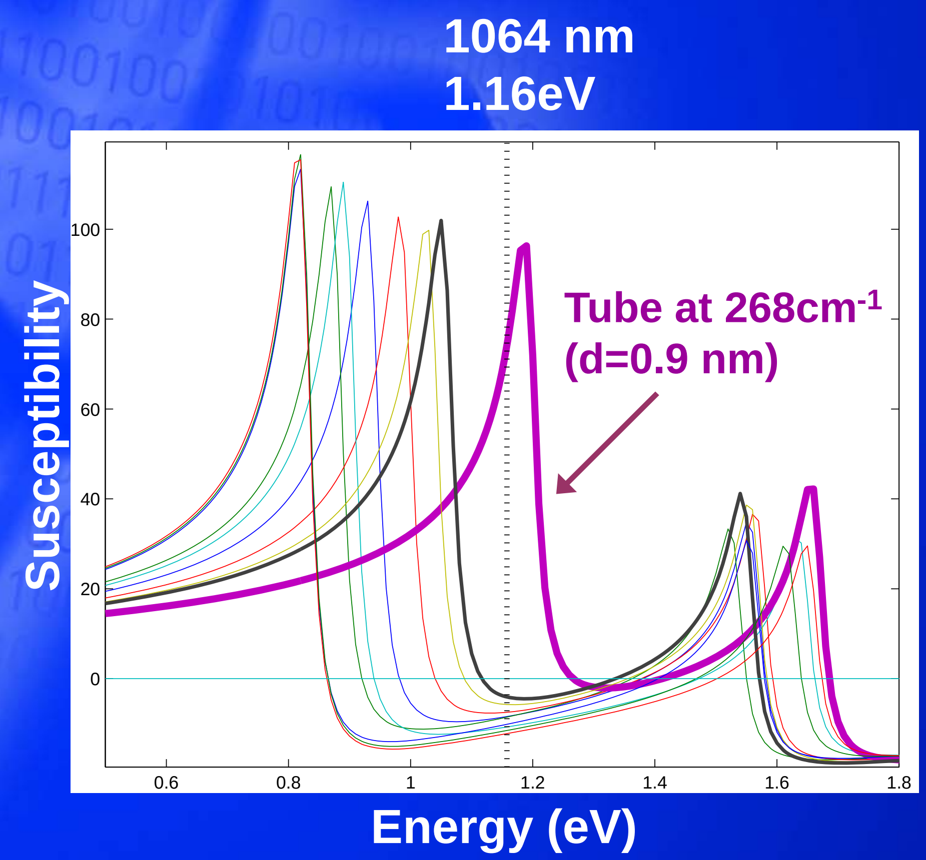



**Enrichment of d = 0.9 nm tubes**

# *In-situ* Raman / Optical Trapping - Theory

Susceptibility of the carbon nanotubes resonant with 785 nm (1.58 eV) Raman laser




- **The susceptibility ($\chi$) of the tubes which are in resonance with the 785 nm Raman excitation are plotted.**
- **At 1.16 eV (1064 nm), the tube at 268 $cm^{-1}$ has the highest $\chi$ compared to other tubes. This is in agreement with the experiment.**



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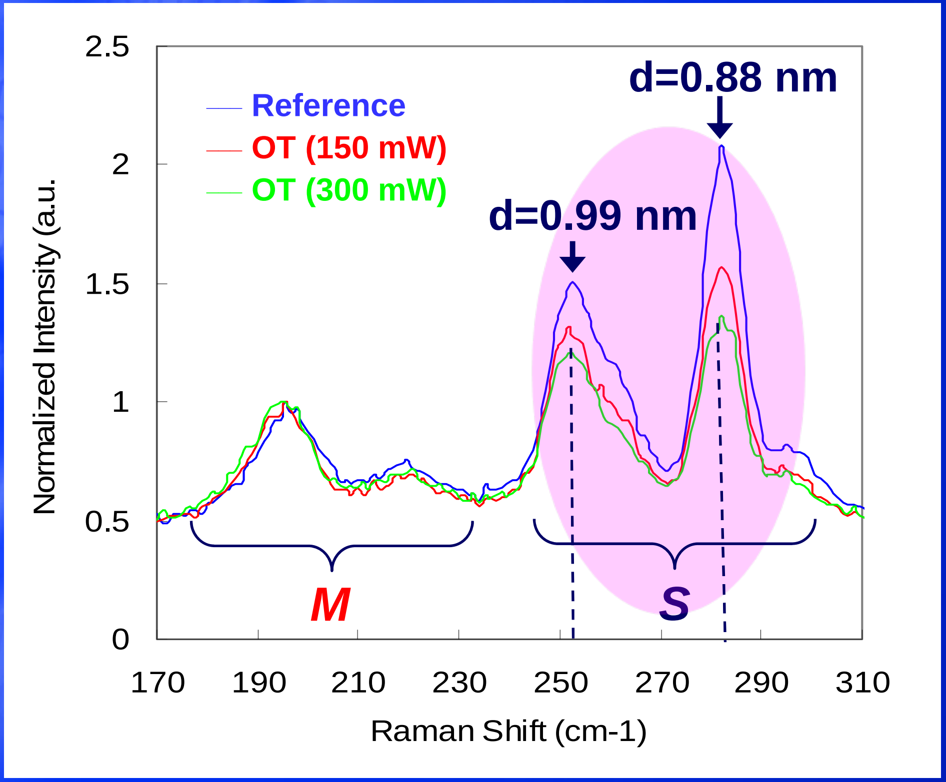
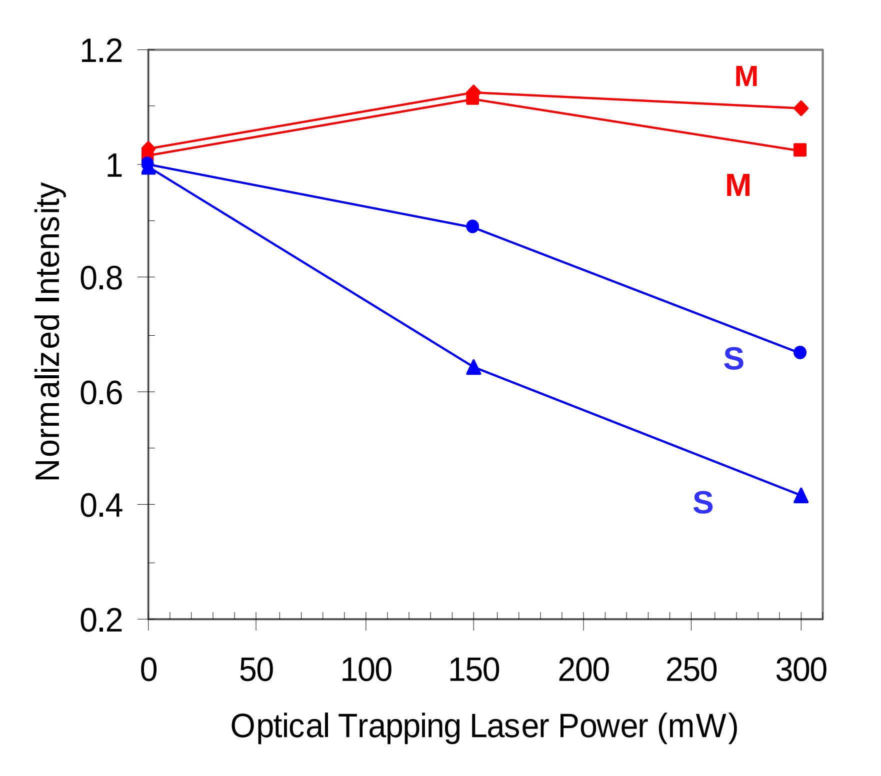
# *In-situ* Raman / Optical Trapping

**DNA-HiPco:*1064 nm trapping, 633 nm probing***




**S-tubes were repelled**



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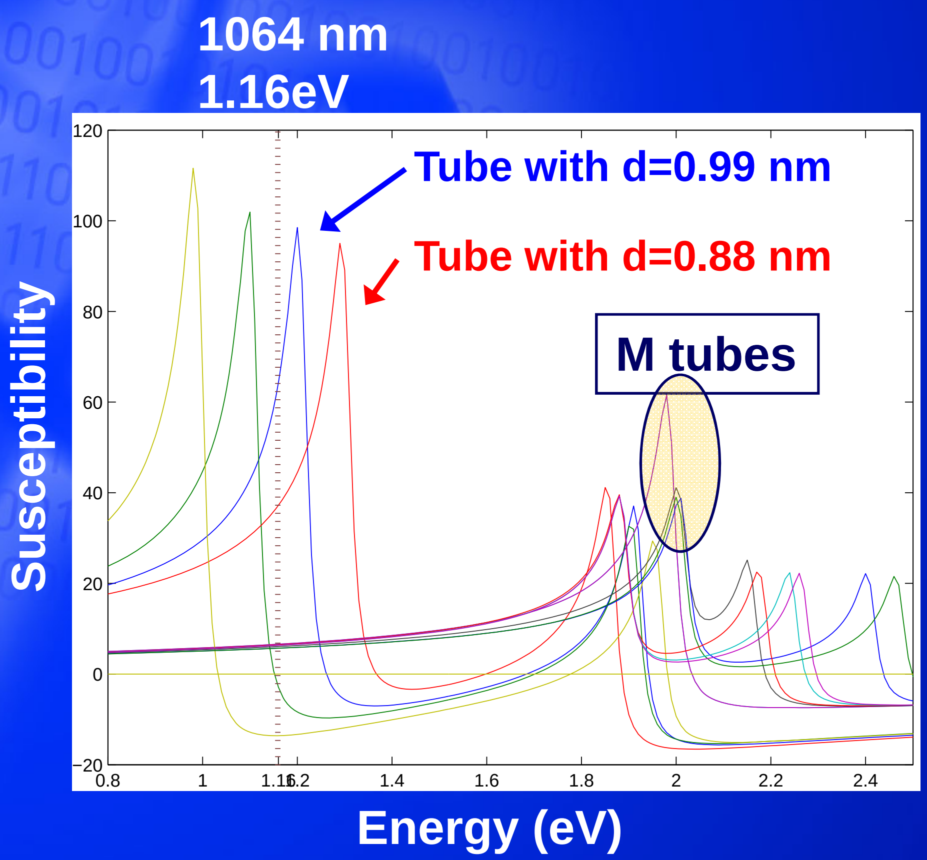
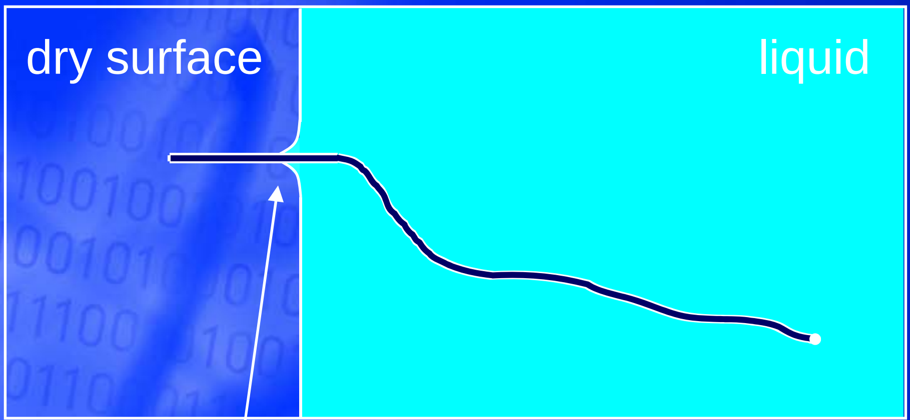
# *In-situ* Raman / Optical Trapping - Theory

Susceptibility of the carbon nanotubes resonant with 633nm (1.96 Ev) Raman laser




- According to the simulation, the $\chi$ for the 0.99 nm tube is larger than the $\chi$ for the 0.88 nm tube, which is somewhat in agreement with the experiment (less repelled).
- But the $\chi$ for the metallic tubes is even lower than that of the semiconducting tubes. This contradicts with the theory

# Other CNT Manipulation Method:
## - CNT Alignment by Molecular Combing

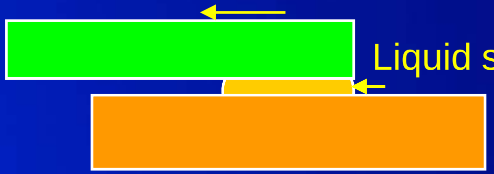


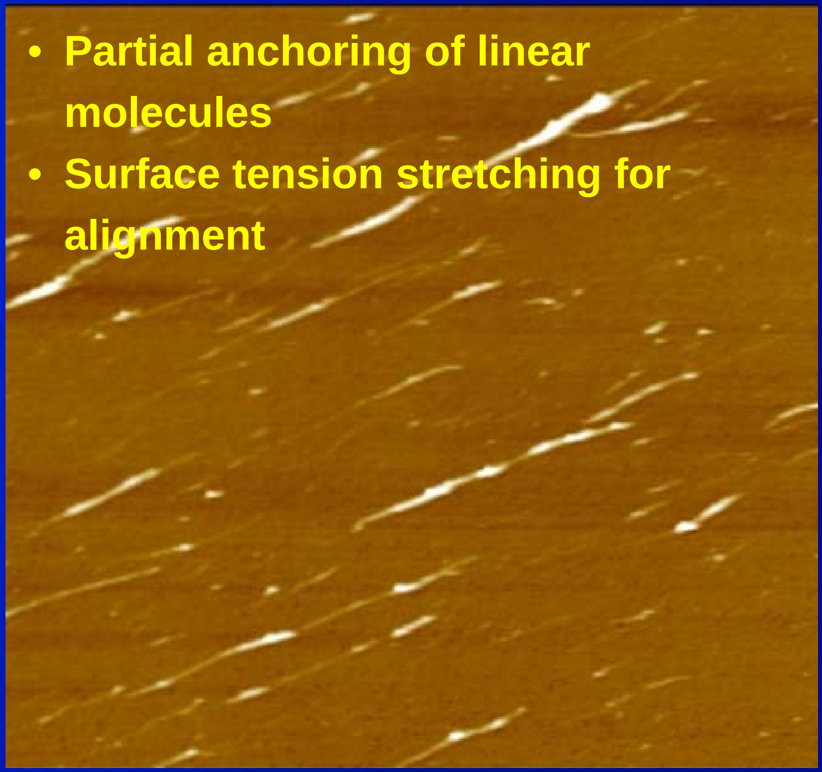

Elastic deformation of contact line

Capillary force: $F_{capillary} \approx \dfrac{\pi \lambda \theta_o^2}{\log L / D}$

Hydrodynamic force: $F_{hydrodynamic} \approx \eta l V$

$$F_{capillary} > F_{Hydrodynamic}$$




(Unpublished data)



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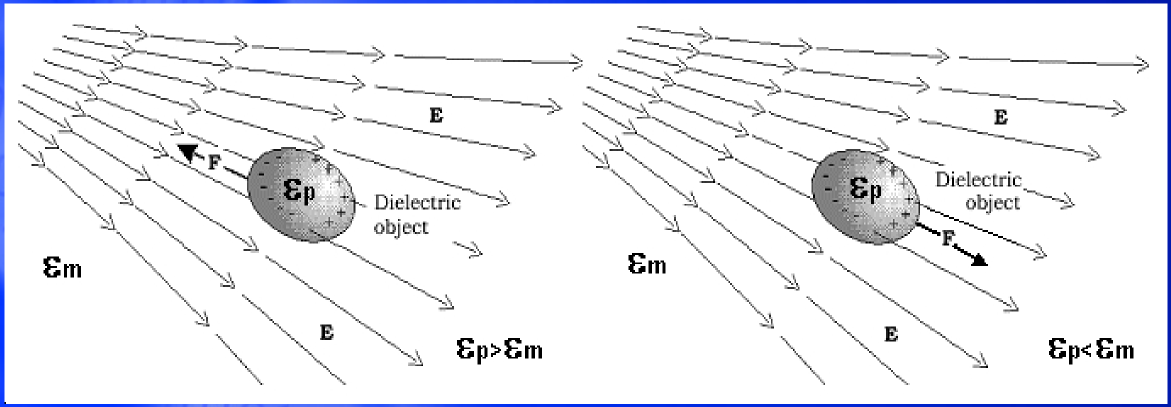
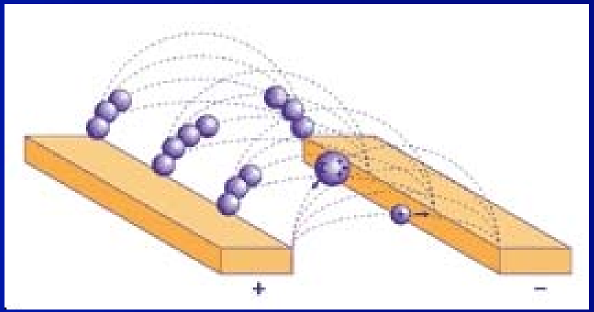
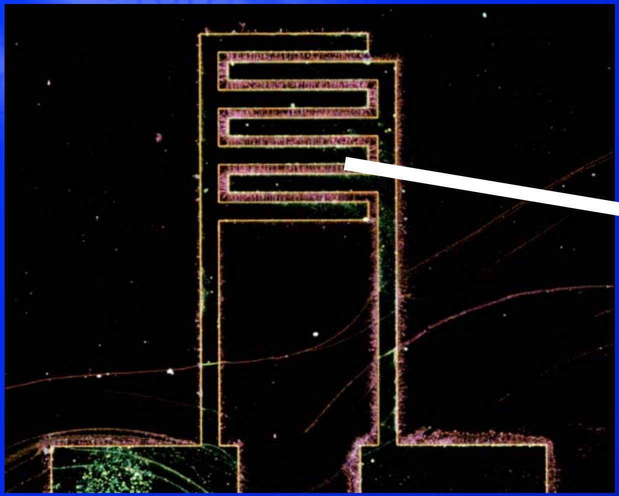
# Other CNT Manipulation Method:
# - Dielectrophoresis

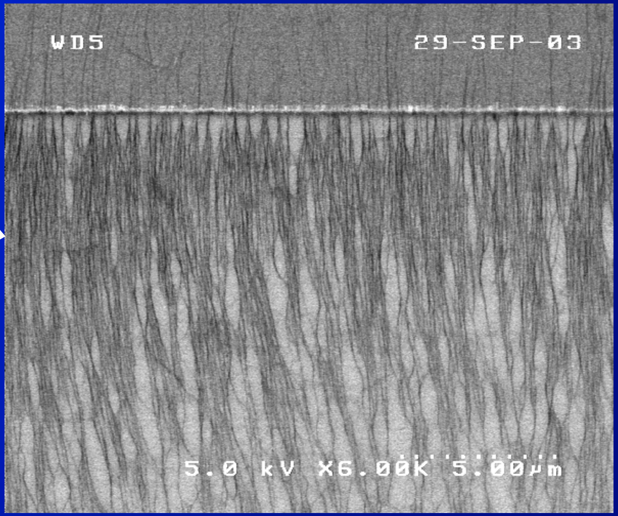
- Polarization and associated motion induced in particles by non-uniform electric field




$$\vec{F}_{DEP} \;\alpha\; \varepsilon_m \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + 2\varepsilon_m} \nabla E^2_{rms}$$






(Unpublished data)



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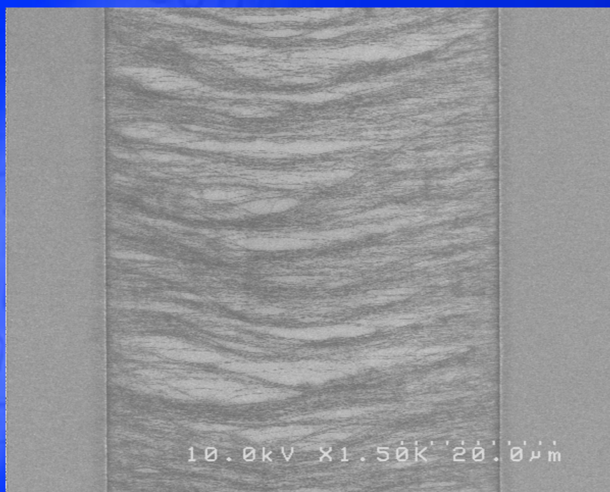
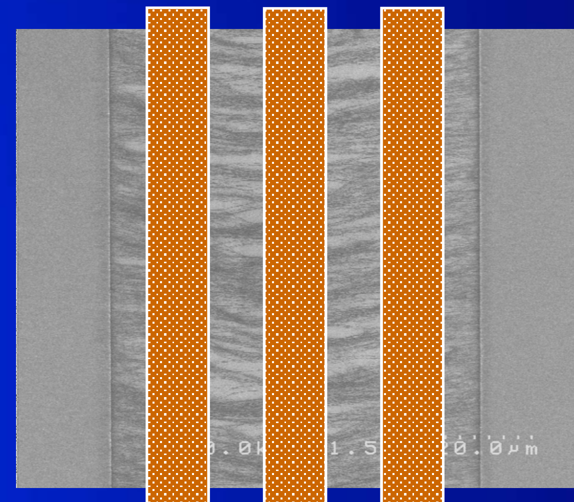
# Future Direction: Controlling Length and End-functionalization

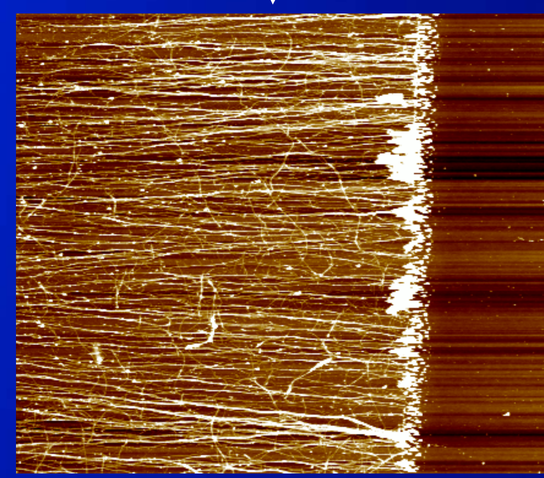


Lithographically defined length

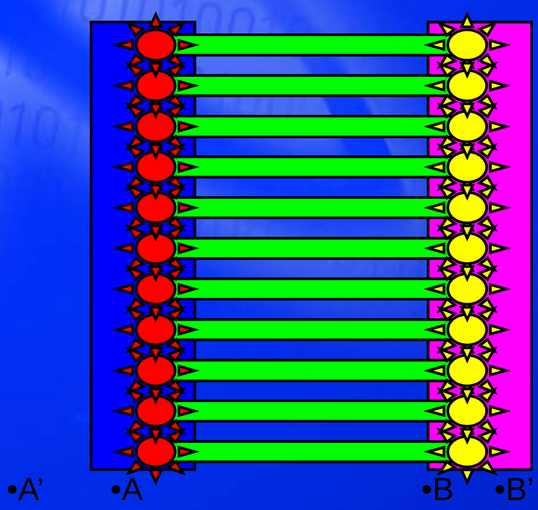
sidewalls protected

$O_2$ plasma etch CNTs



End-functionalization

Self-assembly




(Unpublished data)



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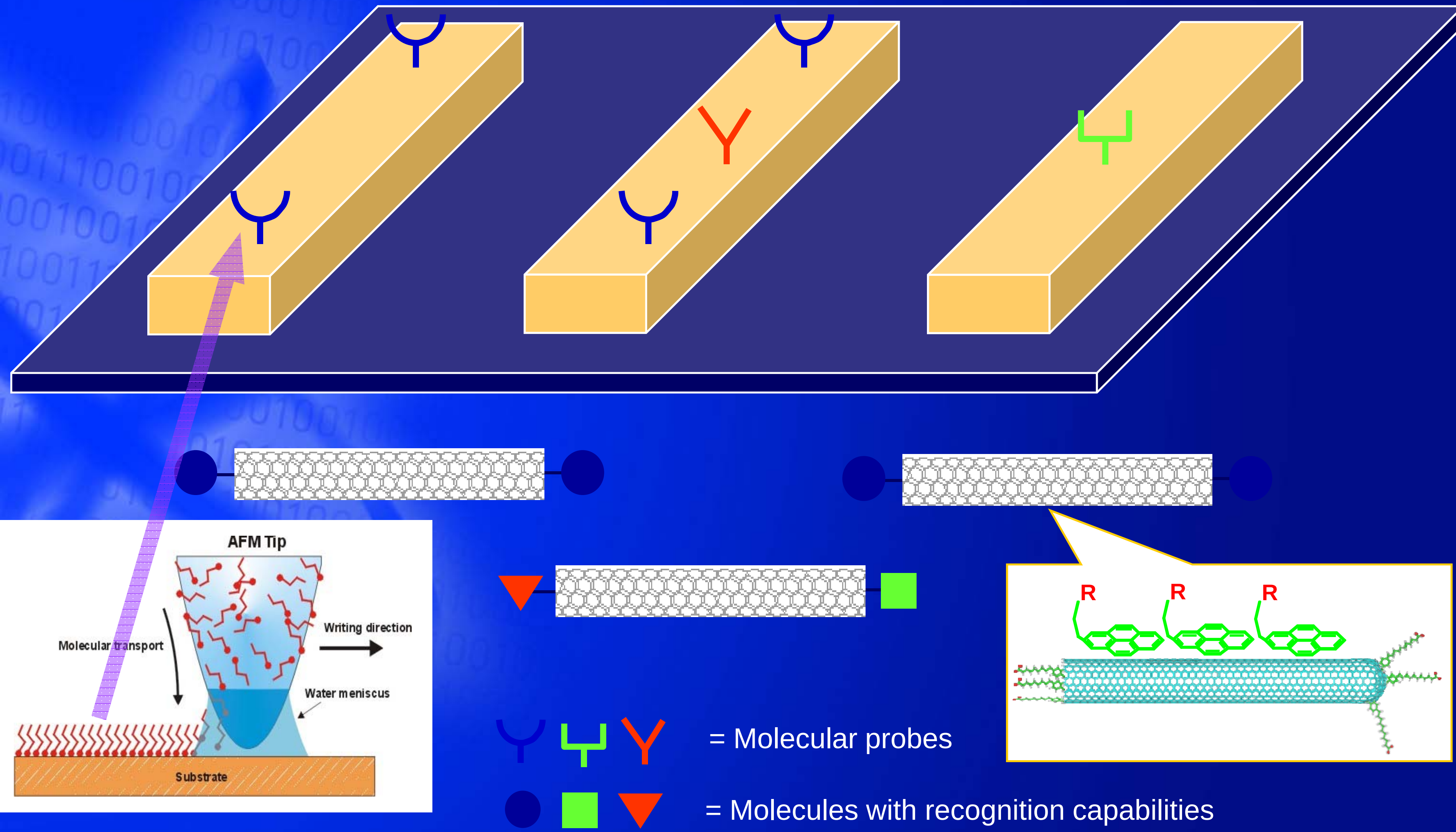
# Future Direction: Bottom-Up Assembly of Molecular Electronics



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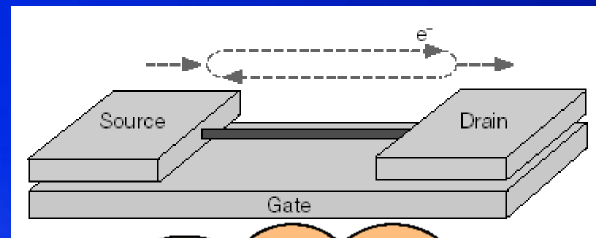
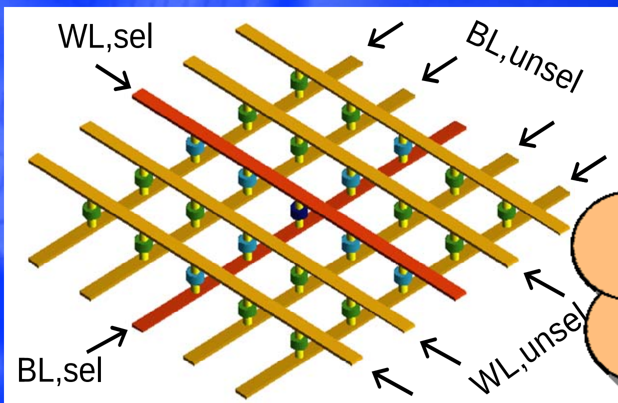
# What could controllable-synthesis and assembly enable?

Quantum logic device

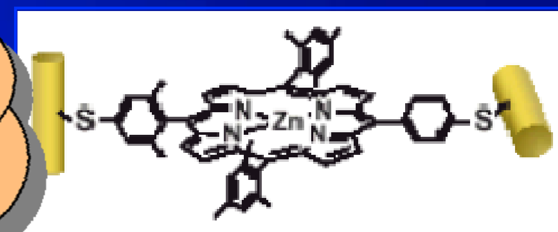


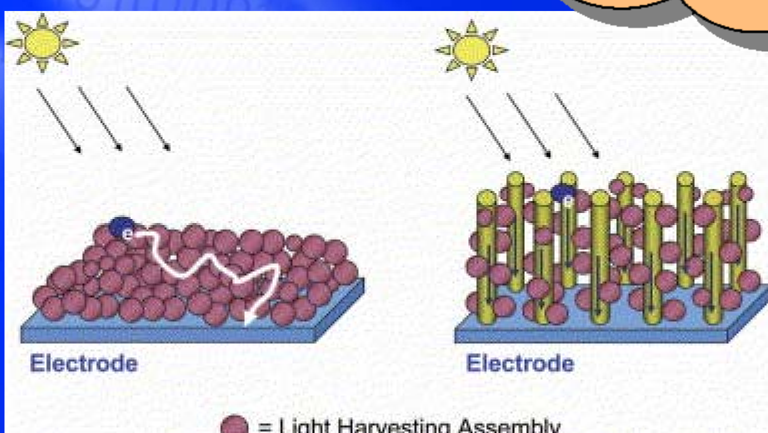

Memory device



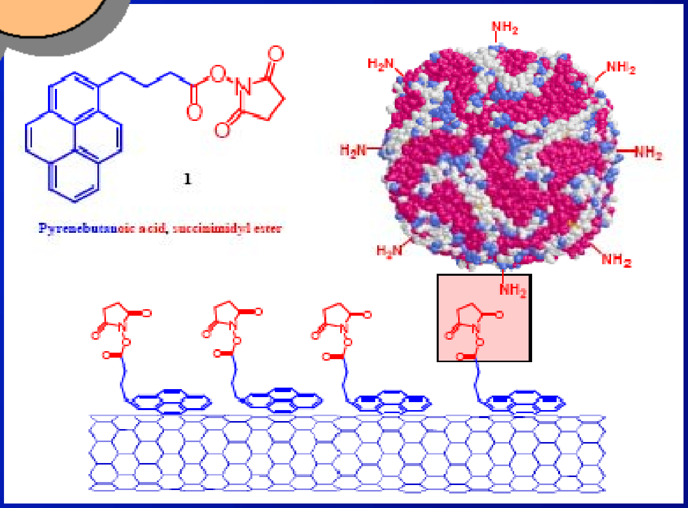

Nanotubes
Nanowires
Quantum
Dots

Molecular device






Energy conversion device




Sensors



Yuegang Zhang

# Summary

- Various methods can be used for nanomaterial synthesis.
- CVD provides great controllability for nanotube device integration using a hybrid approach.
- Excellent performance demonstrated for nanotube based transistors and memory devices.
- Great progress made in electrical contacts for nanotube devices.
- Obtaining electronically pure (single chirality) nanotubes and regular array assembly remain to be two major challenges for high-volume manufacture.
- Bio-inspired functionalization and self-assembly provides great opportunity in addressing these challenges.
- No boundaries in nanoscience and nanotechnology for physicists, chemists, and biologists.

# Acknowledgement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**Intel Carbon Nanotube Strategic Research Team Members:**

Yuegang Zhang (Project Leader)
Shida Tan
Herman Lopez
Robert Chen
Michael Stewart
Victor Brar (intern, MIT / UC Berkeley)
Udayan Ganguly (Intern, Cornell Univ)
Colin Cai (visiting researcher)
Marci Liao (visiting researcher)
Edwin Kan (visiting professor, Cornell Univ)



**Other collaborators:**

J. Guo (Univ of Florida)
N, Teyabi (Intel/UIUC), Y. Narui (Caltech), P. Collier (Caltech), K. Giapis (Caltech)