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# Nanotube Mechanics

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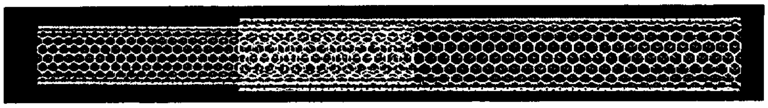
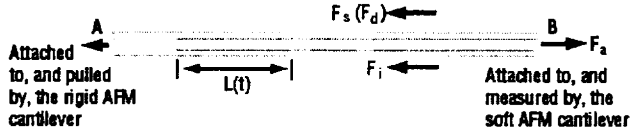
## Shear Strength and Nanotribology



- MWCNT is a perfect object for the study of friction in nanoscale.
- MWCNT consists of nested cylinders of single wall carbon nanotubes that can be conceptual as cylinders rolled from graphene sheet. The layer-layer separation is about 0.34 nm and the layer-layer interaction is due to van der Waals forces.
- Nested tubes in MWCNT can have same or different helicity.

## Sliding Between Nested Shells



- Shear force $F_s = \tau A$, A is the contact area = $\pi d L(t)$.
- Interface force $F_i$: 1. Capillary force; 2. Edge effect force. It only depends on the perimeter length of the nanotube cylinder.
- So $F_a = \pi d \tau L(t) + F_i$. From the $F_a$ versus L(t) dependence, $\tau$ can be obtained.

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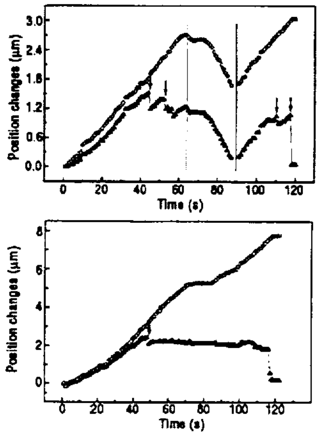
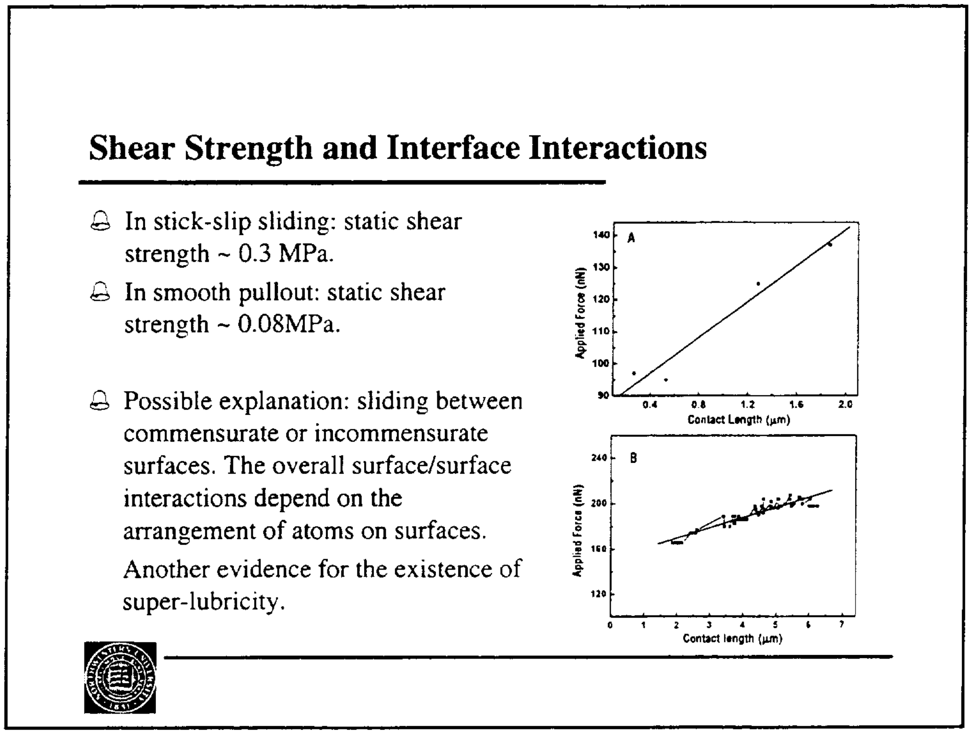
## Stick-Slip and Smooth Pullout

- The position change at each end of the MWCNT is recorded.
- Stick slip sliding: static friction > dynamic friction.

  Smooth sliding: static friction = dynamic friction (normally both are small).

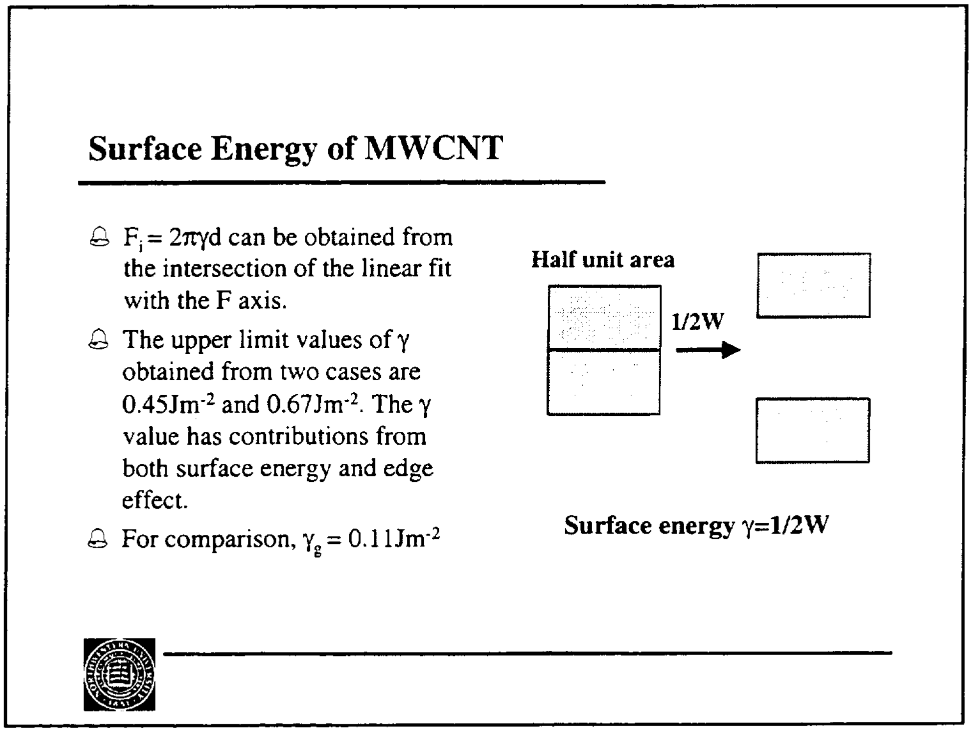




## Shear Strength and Interface Interactions

- In stick-slip sliding: static shear strength ~ 0.3 MPa.
- In smooth pullout: static shear strength ~ 0.08MPa.
- Possible explanation: sliding between commensurate or incommensurate surfaces. The overall surface/surface interactions depend on the arrangement of atoms on surfaces.

  Another evidence for the existence of super-lubricity.



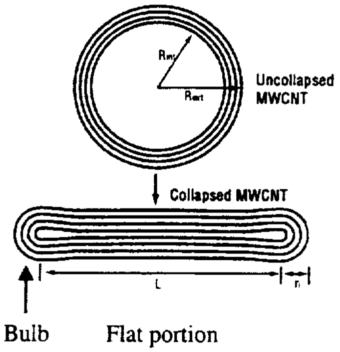
## Surface Energy of MWCNT

- $F_i = 2\pi\gamma d$ can be obtained from the intersection of the linear fit with the F axis.
- The upper limit values of $\gamma$ obtained from two cases are $0.45 Jm^{-2}$ and $0.67 Jm^{-2}$. The $\gamma$ value has contributions from both surface energy and edge effect.
- For comparison, $\gamma_g = 0.11 Jm^{-2}$

**Surface energy $\gamma$=1/2W**

## Radial Deformability of Carbon Nanotube

- Nanoscale objects are excellent candidates for revealing nanoscale interactions.
- The collapse of carbon nanotube relates to:
  strain energy
  van der Waals interactions.



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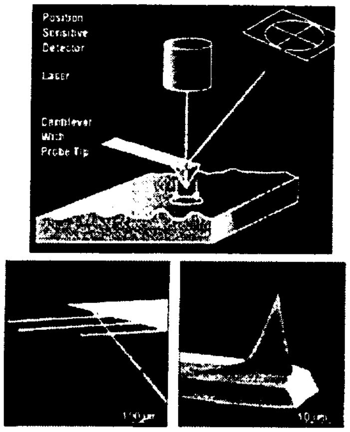
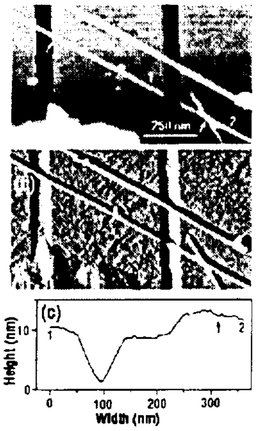
## Atomic Force Microscopy

- Invented in 1986 with the help of good vibration isolation, piezo-materials and electronics.
- Sensitive to the atomic interactions (pN to μN) between the force sensing probe tip and the studied surface.
- Lateral resolution up to 0.1nm and vertical resolution up to 0.01nm.



## Collapsed Carbon Nanotube

- The collapsed nanotube is significantly more flexible than the uncollapsed nanotube; it drops ~ 8nm into the trench.
- Collapse initiates at the bend and terminates before crossing the trench.
- The height of the collapsed nanotube is ~ 2.3nm; the uncollapsed nanotube is ~ 6.5nm.



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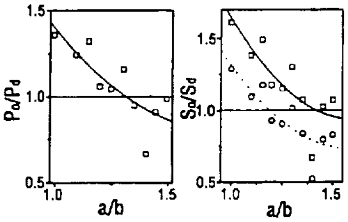
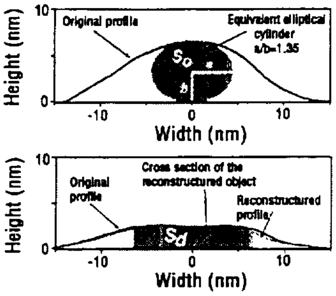
## Structural Analysis

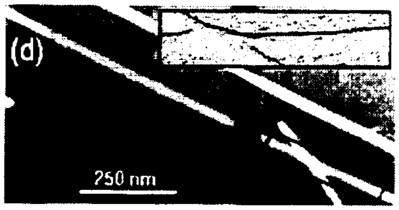
- Erosion and dilation is used to get the true shape of the MWCNT.
- Perimeter fitting and area fitting indicate that the nanotube is a MWCNT having three cylinders.





## Metastability of Carbon Nanotube

- Metastability is the nature of some cylindrical carbon nanotubes having certain types of structures: certain diameters, certain number of walls.



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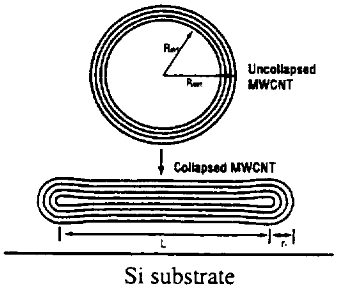
## What Can It Tell Us

- The energetic:

  Strain energy increase $\Delta E_s = E_b - E_{nt}$

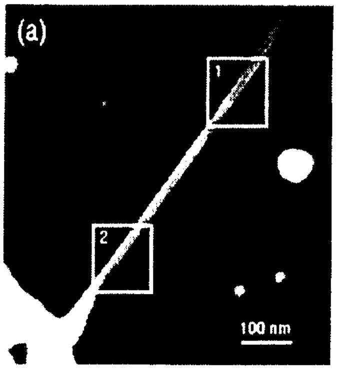
  Surface energy decrease $\Delta E_v = E_{nv} + E_{snv}$

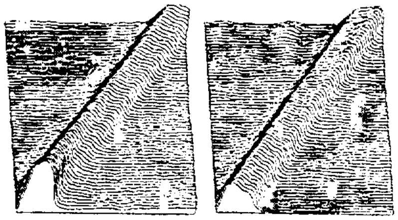
  where $E_b = \pi k / r_i$, $E_{nt} = \pi k / R$, $E_{nv} = -2\gamma L$, $E_{snv} = -W_{sn} L$
- If $\Delta E_s + \Delta E_v < 0$, collapse is favored.
- $\Delta E_s = 36 eV/nm$, $\Delta E_v = -12 eV/nm - W_{sn} L$
- We need $W_{sn} > 2.8 eV/nm^2$(or $440 mJ/m^2$)
- $W_{sn} = 2(\gamma_{si}\,\gamma_g)^{1/2} = 785 mJ/m^2$



## Twisted and Collapsed Nanotube

- Rarely observed.
- More information can be obtained from the twisted nanotube. Good for theoretical simulation.





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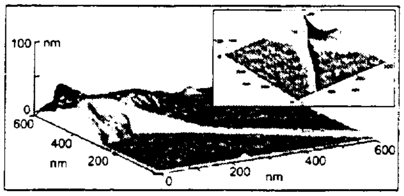
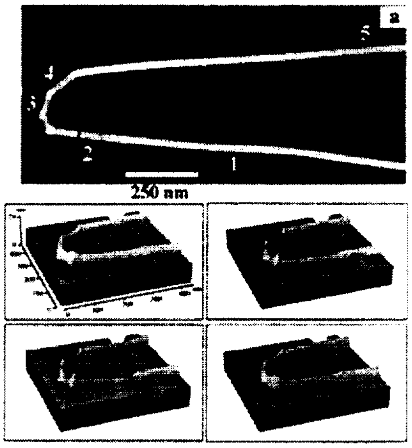
## Anisotropic Mechanical Properties

- Anisotropic mechanical property is also present in collapsed nanotube depending on its orientation.
- Two factors: the different moment of inertia ($\propto wd^3$) and the different elastic constant.



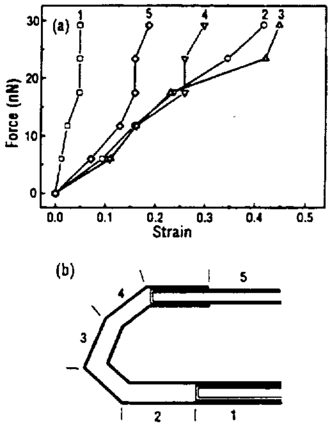
## Dynamic Study of the Deformability

- Dynamic compressing of individual MWCNT is performed and recorded.
- It reveals different rigidities along the MWCNT.



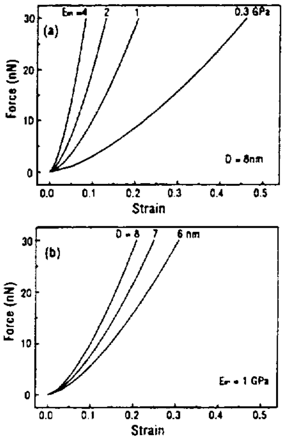
## Structural Information

- The applied force by AFM tip is calibrated in a separate experiment and in a simulation.
- The obtained force-stain curve indicates that MWCNT is relatively soft in its radial direction and sensitive to the structure.



## Mechanical Property in the Radial Direction

- A simplified model is used to estimate how MWCNT can be compared to other solid materials.
- MWCNT is considered as a elastic cylindrical rod and AFM tip as a sphere. Hertz model is applied to solve the contact problem.
- MWCNT is comparable to an elastic rod having Young's modulus around several GPa; for example, rubber, polymer.



## Conclusions

- New tools and methods are developed for studying carbon nanotubes.
- First measured the tensile strength: ~ 30 GPa.
- Young's modulus ~ 1000 GPa.
- First measured the shear strength: around 0.3 MPa or 0.08 MPa depending on the degree of commensurance between neighboring shells.
- In the radial direction, carbon nanotube is deformable having an effective Young's modulus value of about several GPa.
- The stability of a carbon nanotube depends on its structure.
- Nanoscale interactions can have significant effects on the behavior of carbon nanotubes (e.g., capillary force, substrate effect, edge effect).

## Further References:

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