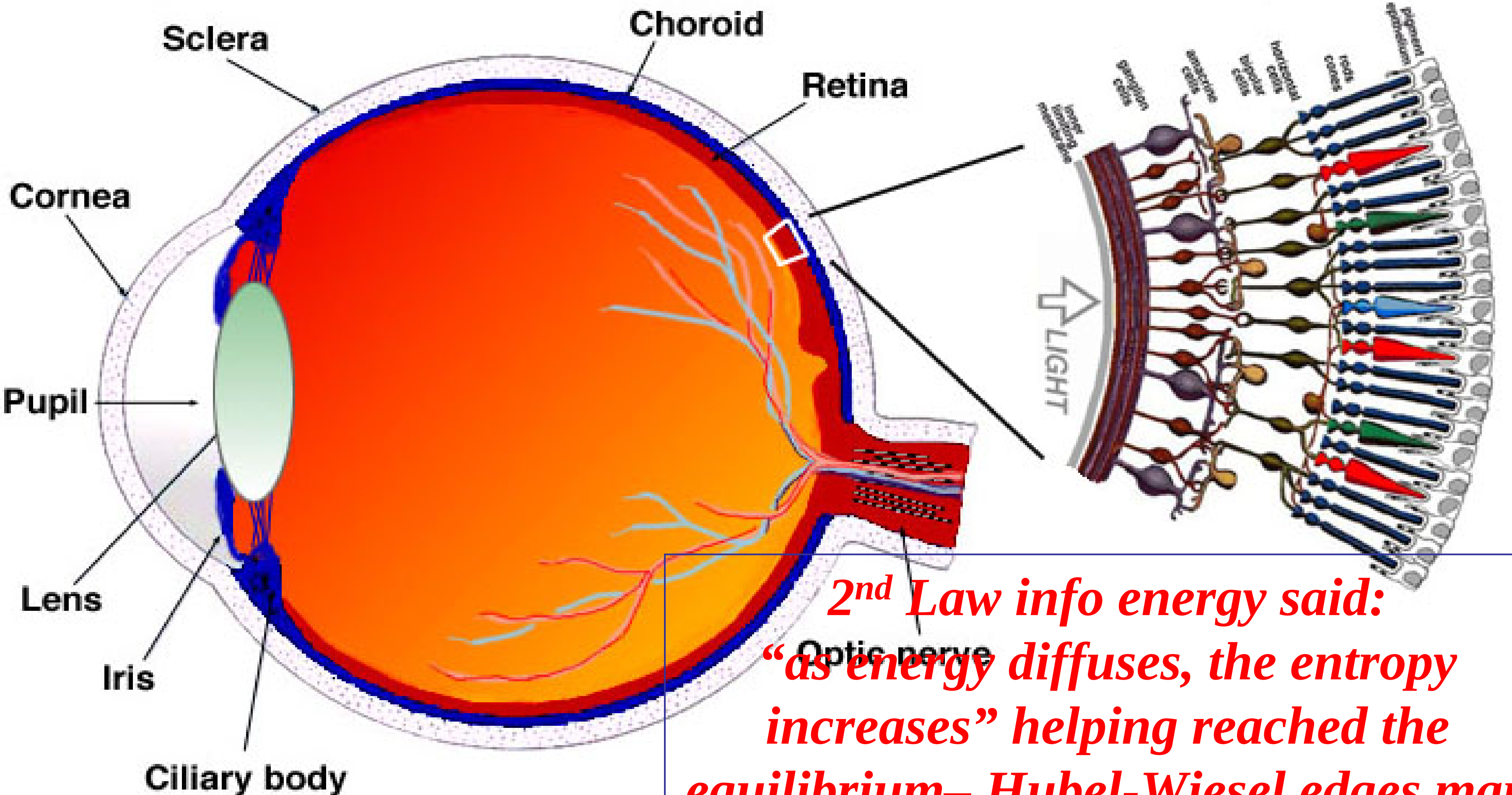
3. Nano Camera Fabrication Technology

Preventive diagnoses must be done regularly at homes.

We need to design non-cryogenic-cooled consumer electronics camera called "(passive non-contact accurate to 0.02 degree) dual infrared) Spectrum Thermometer TM" replacing traditional contact thermometers based on either thermal coupler or Mercury thermometer

Nano-photonics must learn from our eyes?

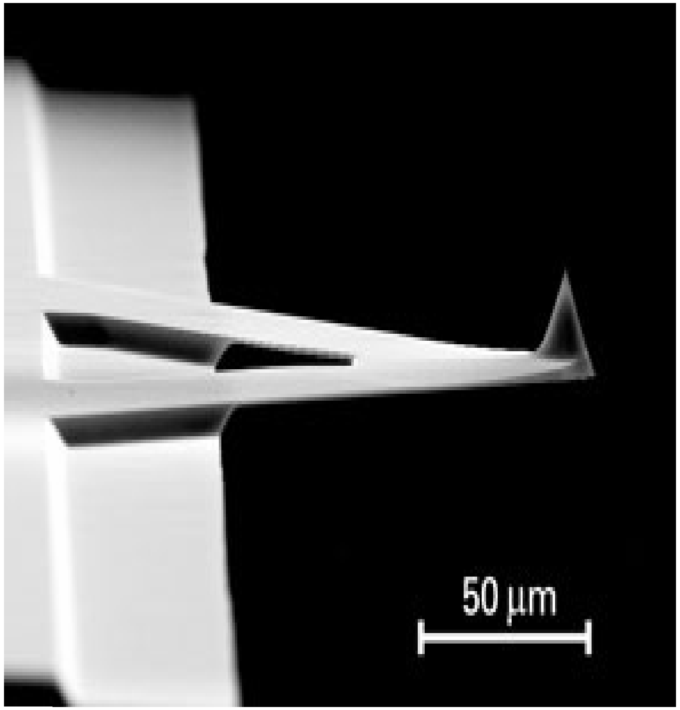
156 millions rods-cones excitations must decay to save energy and make room for further excitations. Pseudo-1-D cone suffers less noise, enjoy single photon detection without Liquid Nitrogen coolant =Nano-photonics need CAD NanoRobot manipulator, from 1 meter to 10^{-9} meter!

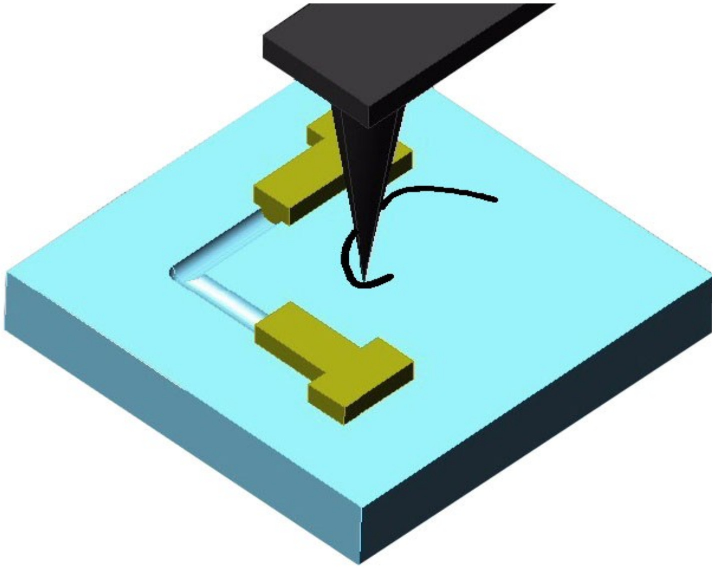


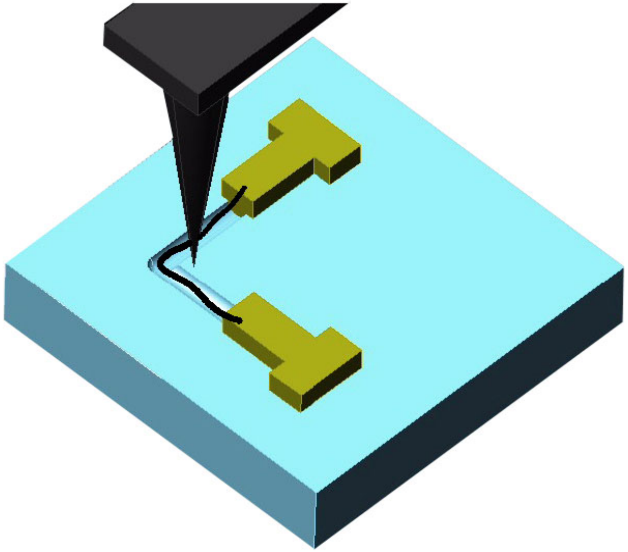
2nd Law info energy said: "as energy diffuses, the entropy increases" helping reached the equilibrium– Hubel-Wiesel edges map

Fabrication of Sensor Pixels

- AFM based nanoassembly
- Pushing Nanotube into nanofixture
- Tuning CNT band gap by modifying its shape







Biomimetic Fovea Camera by means of Carbon Nano Tubes overlayed CCD array

(1) Implementation issue:

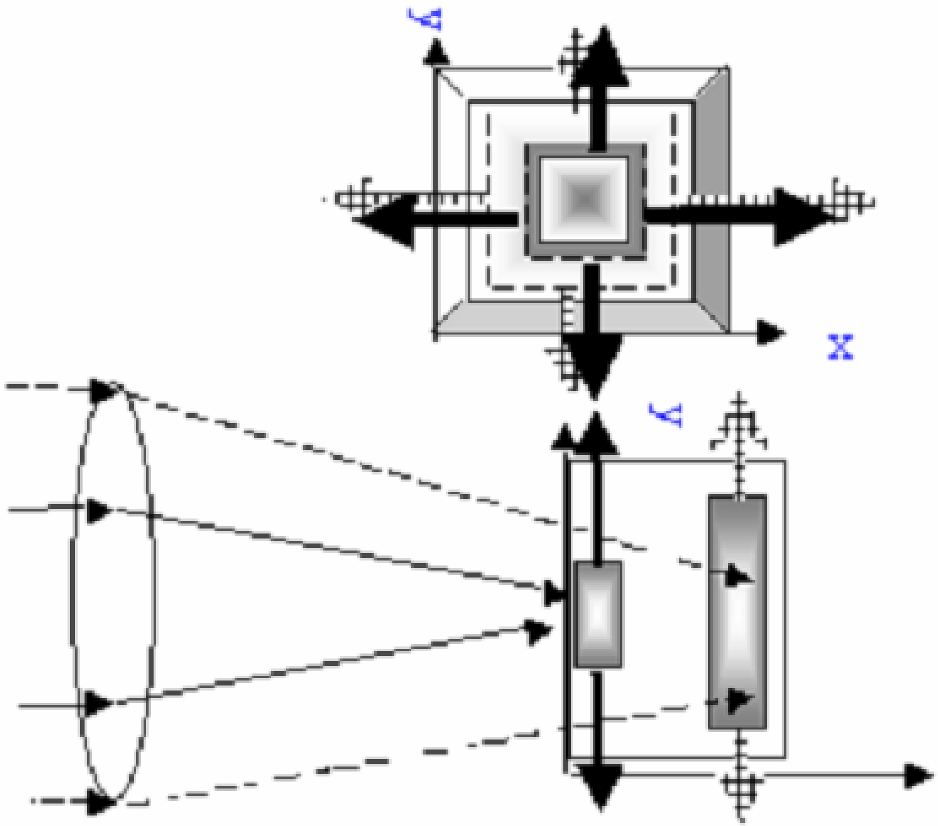
nano-robot

(2) Algorithm issue:

unsupervised Fusion

Non-Cryogenic Co-Axial Fovea Design of Infrared Two Color Pixels Planes*

- full-band IR lens focused at dual focal planes along uniaxial for both MidIR &LongIR
- Band-selective Carbon NanoTube (CNT) generates only 1% or less occlusion over Long IR PFA CCD pixel.
- CNT might only suffer 1D noise that permits a non-cryogenic cooling.
- Un-cool FPA CCD for LongIR & steering & pointing at ROI
- Unsupervised fusion for unbiased feature extraction.



Uncooled night vision

CCD @$1K

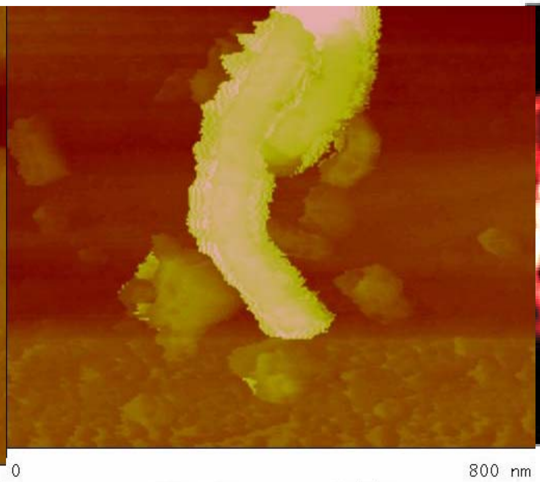
*Szu et al. Patent Disclosure 2004

Non-cryogenic Spectrum Thermometer based Mid-IR 1-D CNT & Long-IR FPA

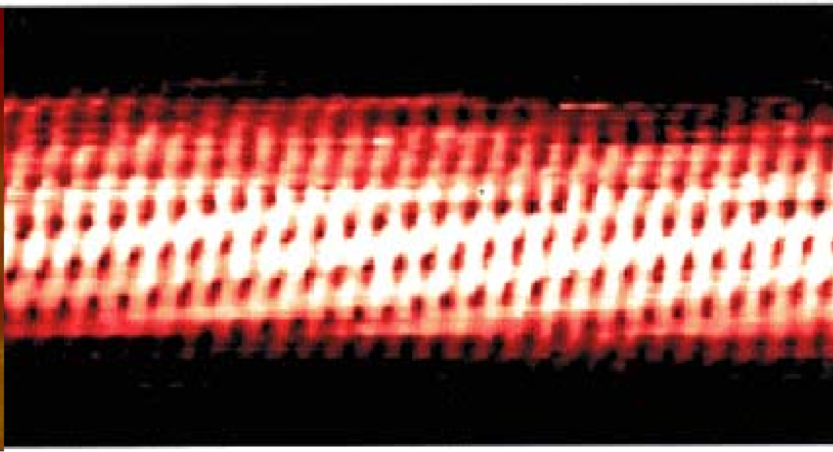
- Navy Patent 2004 unsupervised fusion by Szu et.al. can provide unbiased feature extraction.
- Un-cooled 2 Color Infrared Camera under $1K can provide mini-UAV new capability and dual usage for family spectrum thermometer for sport medicine and early tumor diagnoses.

CNT (S. Iijima, CNT, Nature 354,56,1991; Nobel Prize: C_{60} Bucky, Rice U. Rich Smoley 1989)

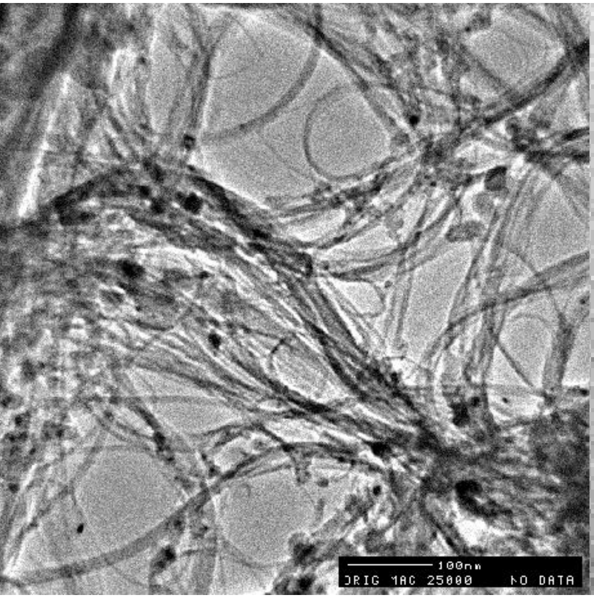
AFM image



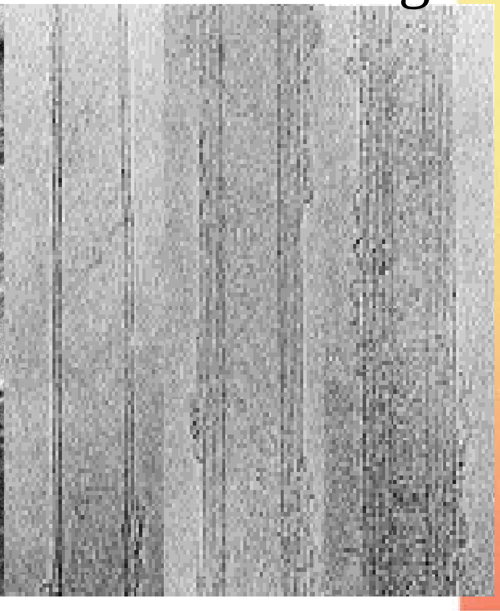
STM image of CNT



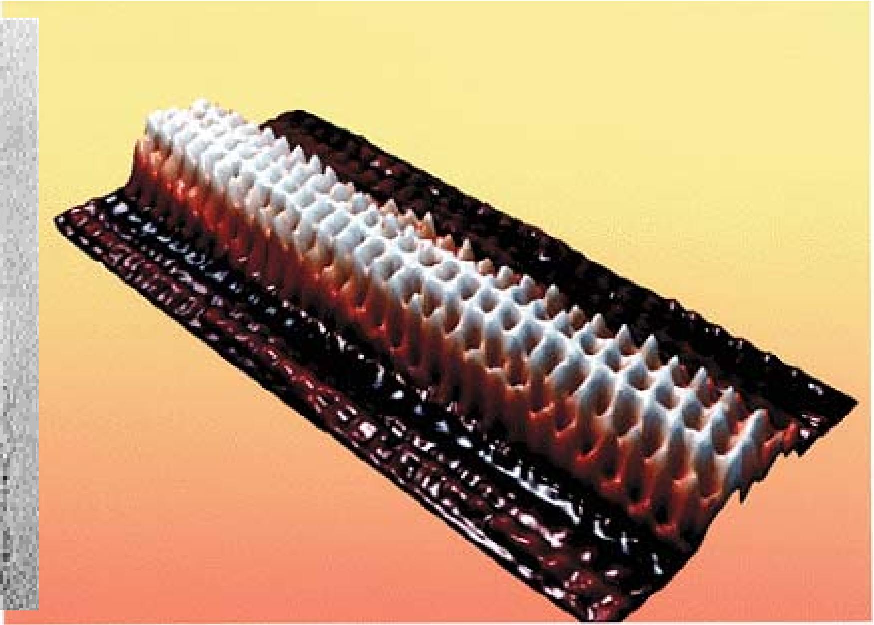
SEM image



TEM image



Cees Dekker, Delft Univ of Tech

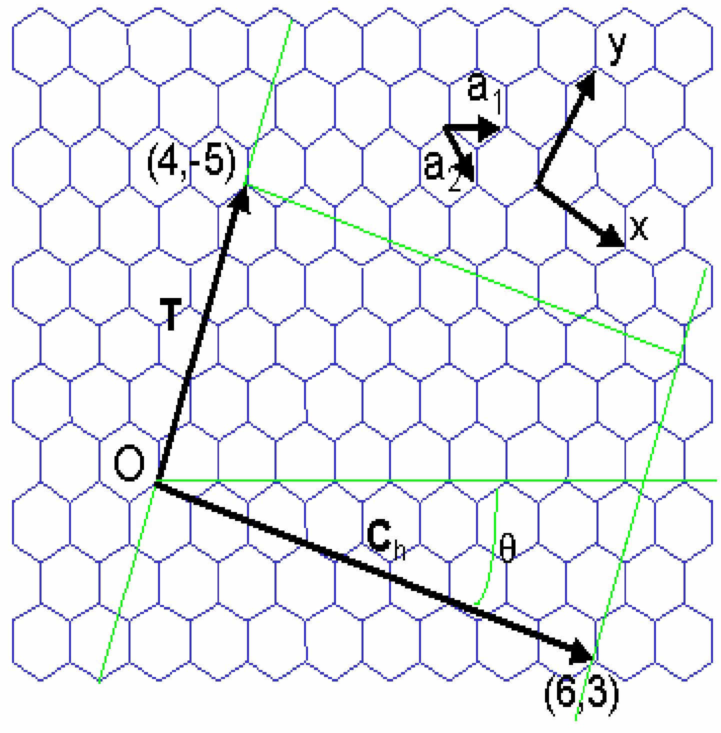


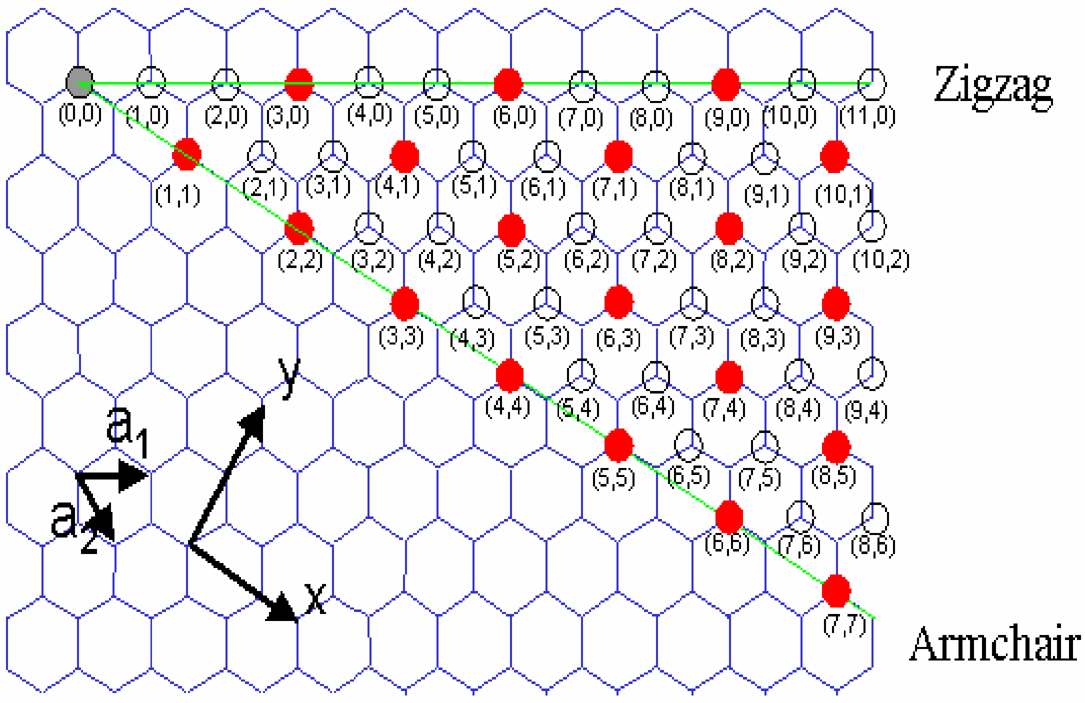
Why Nano technology CNT for double color Infrared Camera?

- Nano 10^{-12} meter is a small quantum system of molecule about 10 Angstrom (10 Dalton)
- It can fit in small space for local action.
- It is at the border of classical physics and quantum mechanics
- It can be either conductor or semiconductor depending density of states exist at Fermi surface or not.
- As a conductor, it has a sharpest field gradient for point discharge for the ionization of neutral gas
- It enjoys limited quantum phonon noise

CNT Index Scheme

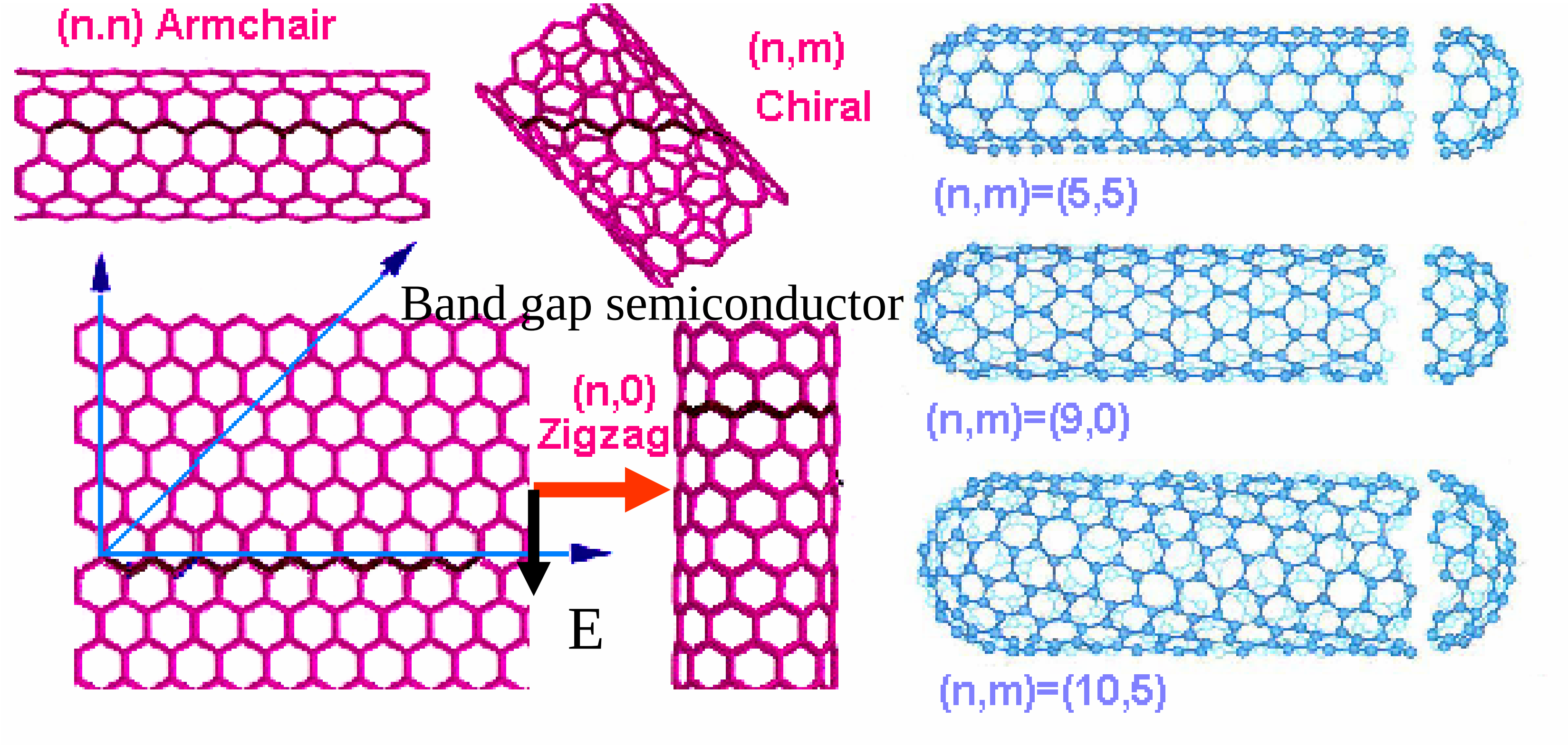
- Folding Chiral vector is defined as $\vec{C}_h = n\vec{a}_1 + m\vec{a}_2$
- The translation vector T is perpendicular to the chiral vector
- (n,m) is the index of CNT





Classification of CNT

- Two major categories : Conductor Armchair (n=m); semi-conductors Zigzag (n=0 or m=0 non-multiple of 3).
- Single-Wall; Multiwall



Dispersion Relation

$$Saito\ et.al.\ \ from\ \ MIT\,(1992\,APL,\,p.2204)$$

$$E_{2D} = \pm\gamma[1 + 4\cos(\frac{\sqrt{3}}{2}k_x a)\cos(\frac{1}{2}k_y a) + 4\cos^2(\frac{1}{2}k_y a)]^{1/2}$$

ρρ

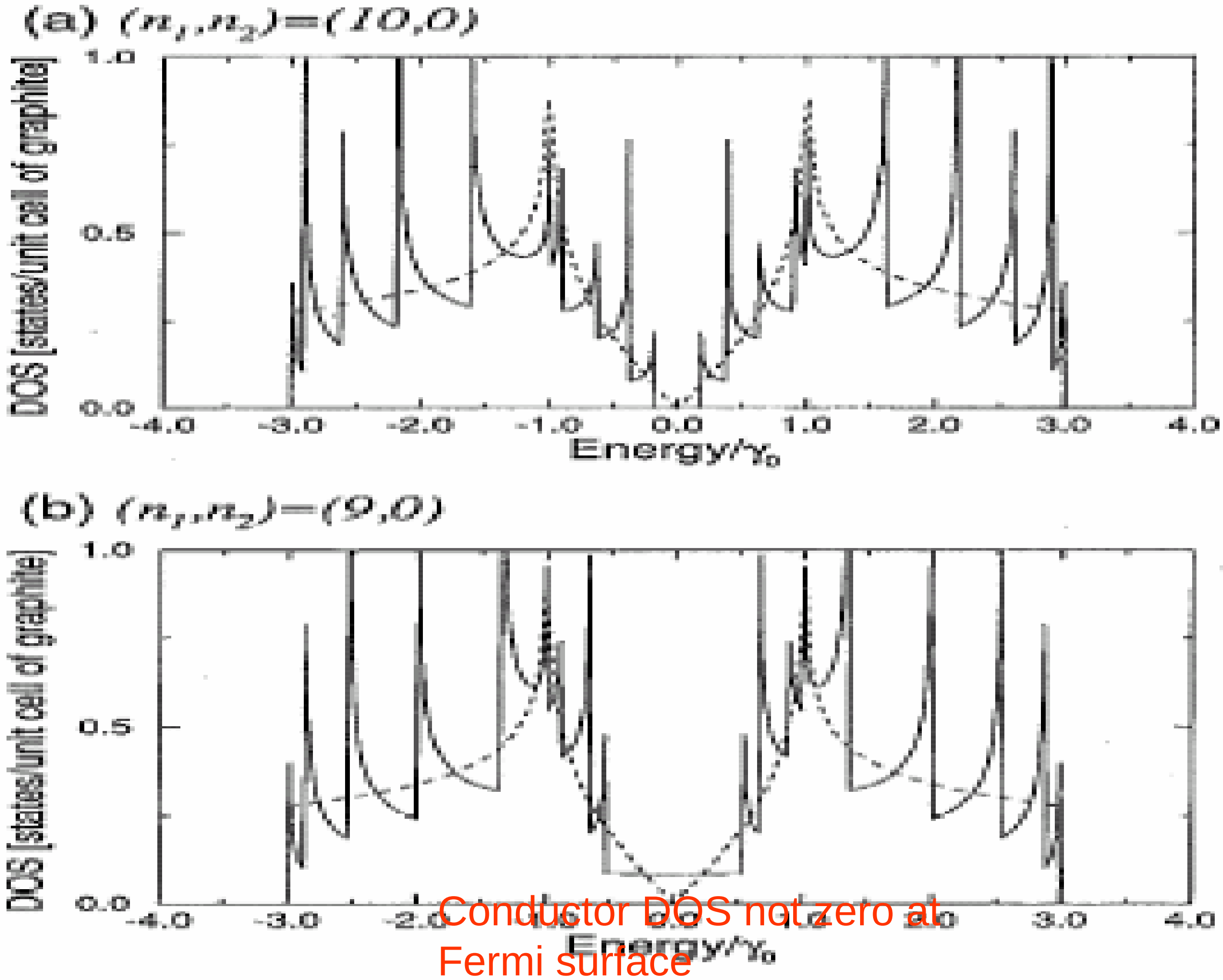
$$Ck = 2\pi\,\mathrm{int}\,egers$$

$$Conductors\,E_F = 0\ \ where\ \ density\ \ of\ \ states \neq 0$$

$$n_1 = n_2$$

$$2n_1 + n_2 = 3x\,\mathrm{int}\,egers$$

Dispersion Relation: Wave Eq. exp(iωt-kx)



Conductor DOS not zero at Fermi surface

FIG. 3. Electronic density of states for two (n_1,n_2) zigzag fibers: (a) (10,0) and (b) (9,0).

Single Photon Detection Design Logic

- Design Logic by means of "negate the converse", "-1x-1=+1"i.e. a single photon can not provide enough signal charge over noise (SNR) but it can nevertheless affect the photoelectric medium to tip or switch the balance of an already existed & balanced so-called dark current driven by internal energy toward a different path, e.g. Wheatstone bridge of 4 arms in balance.

Middle Infrared Implementation Material

- Biomimetic Implementation: 1-D Quantum Carbon Nanotubes (CNT) in zigzag crystalline state enjoys bandgap semiconductor, which can be tuned by radius selectively at MidIR spectral.
- Working Hypothesis: CNT should suffer less thermal noise owing to a restricted geometry of noisy phonon excitation (TBD).

Single photon SNR Quantum eff.

CNT bandgap at Mid IR 3 to 5 micrometer

$$Signal\ \ photon\ \Delta E = \hbar\omega = h\frac{c}{\lambda} = 0.414eV \Leftrightarrow 0.248eV$$

$$Between\ \ room\ temperature\ \ T = 300^{o}K;\ \ Liquid\ Nitrogen\ T = 77^{o}K$$

$$Gaussian\ \ noise\ \ energy\ K_B T = \tfrac{1}{40}eV = 0.025eV;\ \ 0.006eV\ a\ \ factor\ 4$$

$$Johnson\ \ \ shot\ noise\ whose\ mean = \mathrm{var}\,iance$$

$$1D:\ \ \frac{1}{2}K_B T < dark\ \ current < 3D:\ \frac{3}{2}K_B T\ at\ room\ temperature$$

Structure Dependency of Bandgap

Mid IR 3 to 5 micrometer

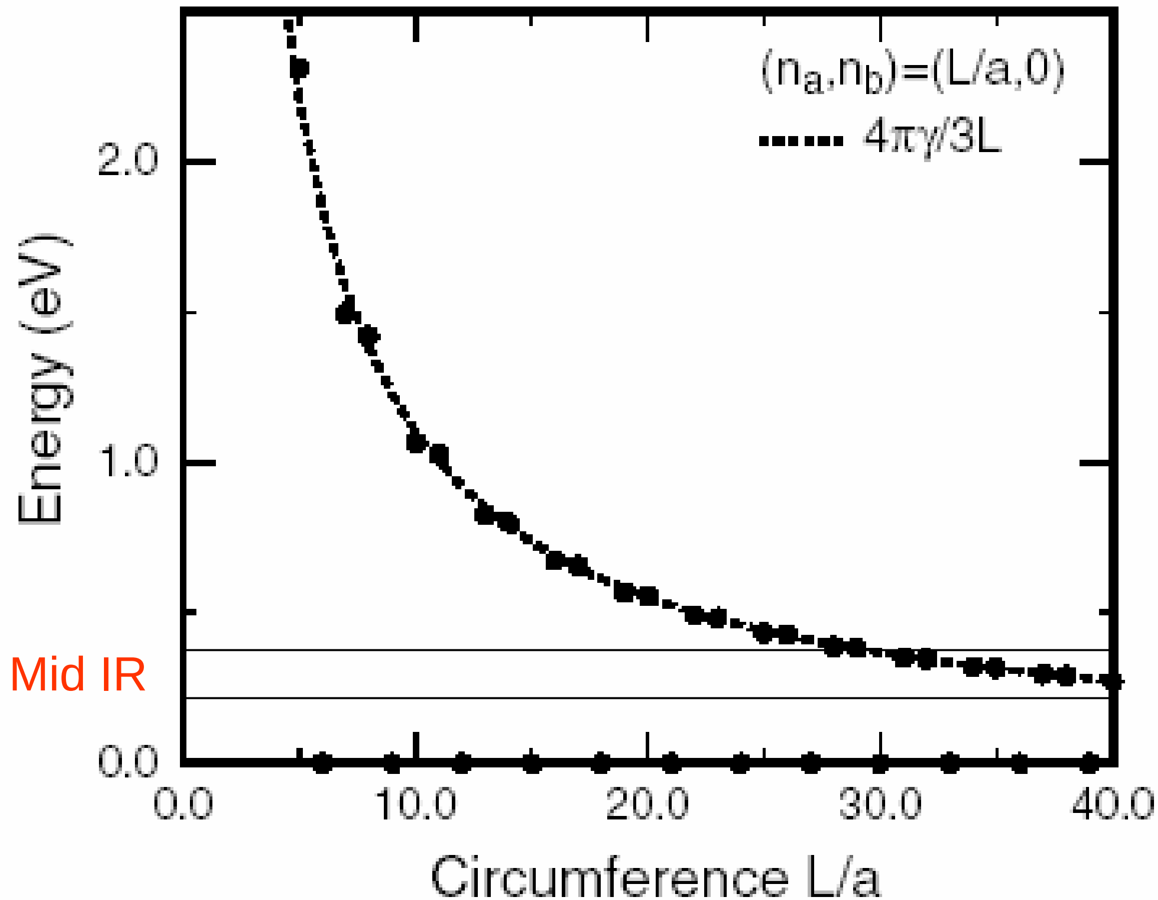
$$Signal\ \ photon\ \Delta E = \hbar\omega = h\frac{c}{\lambda} = 0.414eV \Leftrightarrow 0.248eV$$

- Armchair (n,n) nanotubes are metals

(Bandgap of zigzag CNT)

- (n, n +3i) tubes (with an integer) are small gap semiconductors with Egap $\propto 1/R^2$

- Other tubes have larger gaps proportional to 1/R



Computation of Bandgap

- Single-wall (CW) CNT

$$E_g = \frac{2\gamma_0 a}{D}$$

γ_o =2.6eV: pp π hopping interaction,
a=1.41Å is the C-C nearest neighborhood distance,
D is the diameter of the SWCNT

- Multi-wall CNT

$$E_g \approx \frac{3}{\sqrt{2}} M_i \varpi^2 \frac{a^3}{D}$$

$M_i \approx 2\text{x}10^{-23}$ is the mass of carbon atom,
$\varpi \approx$1600cm^-1 is the characteristic phonon frequency

Grand Challenge:
Un-cooled Mid IR SNR 5 orders of Magnitude

Time integration of 100 signal photons is needed

$$1-D\ dark\ current\ \frac{1}{2}KT << 3-D\ dark\ current\ \frac{3}{2}KT$$

$$0.0125eV < dark\ \ current < 0.0375eV$$

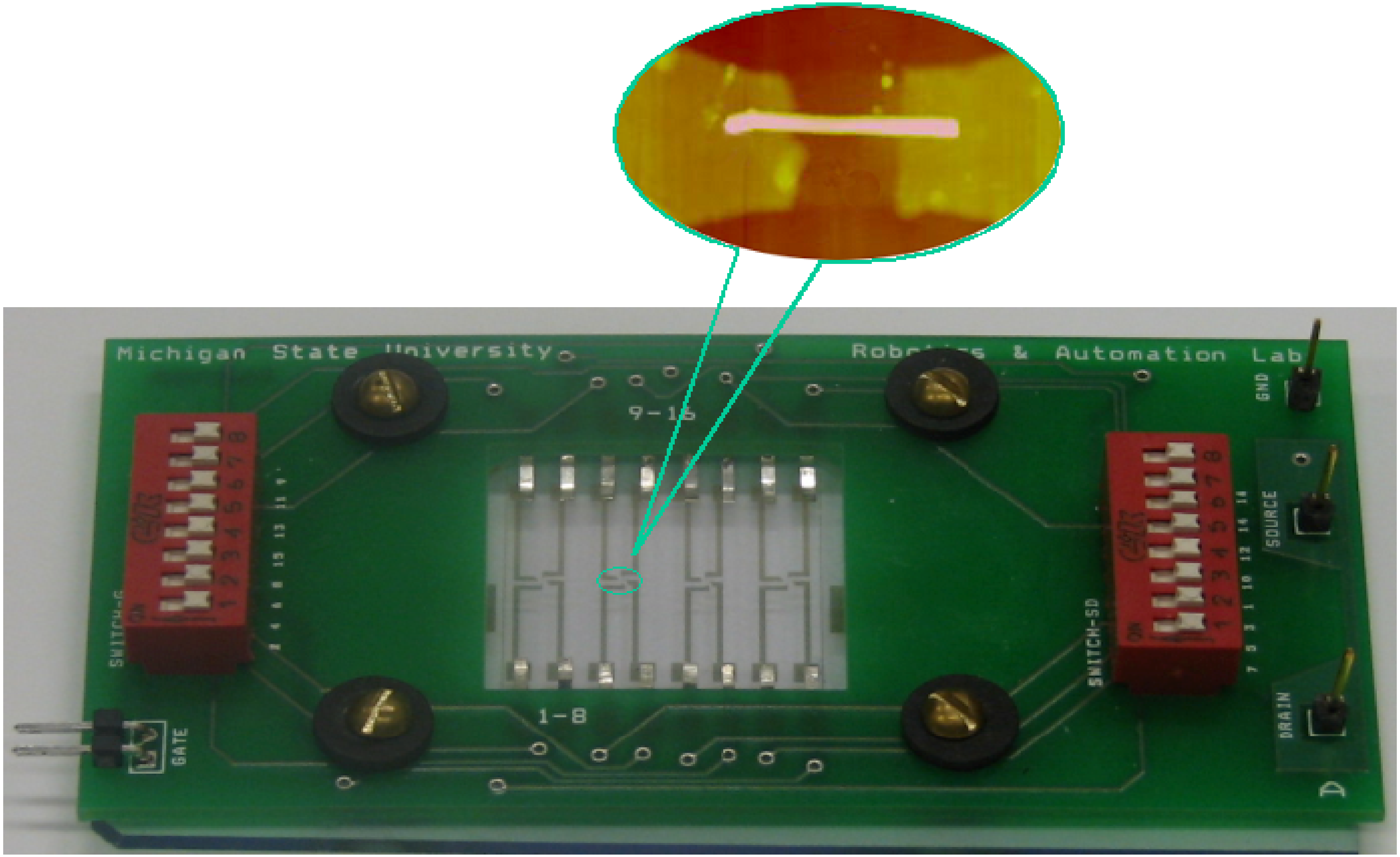
$$SNR_{room} = \frac{0.4 \Leftrightarrow 0.2}{0.01} = 40 \Leftrightarrow 20\ if\ 1-D\,(otherwise: 13 \Leftrightarrow 7\ for\ 3-D)$$

$$at\ 77^{o}K \Rightarrow noise\ 0.006x3/2 \cong 0.01\ \ (1\%\,eV)$$

$$SNR_{cryogenic} = \frac{0.4 \Leftrightarrow 0.2}{0.01} = 40 \Leftrightarrow 20\ if\ 3-D$$

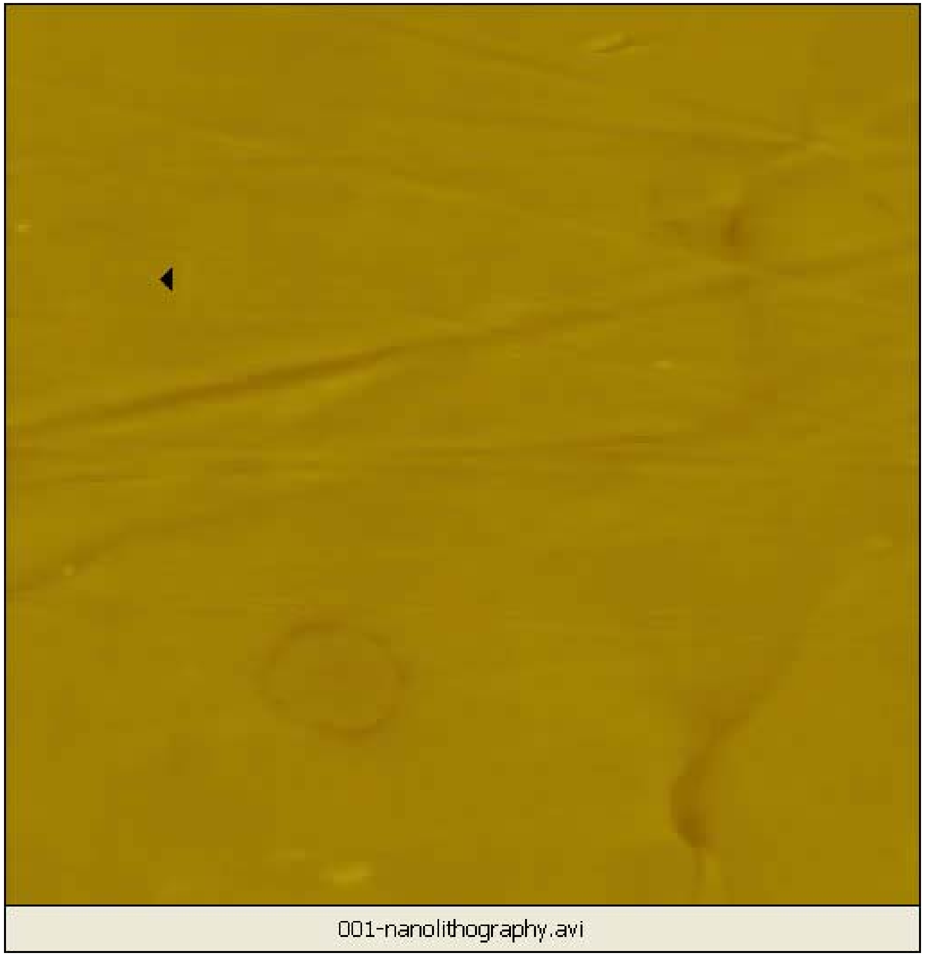
Classical Nanostructure 1/f noise vs. Quantum CNT Lorentz noise

- Wiener-Khtchine Theorem $FT\{psd(f)\}=\langle c(x_o+x)c(x_o)\rangle$
- Nanowire, e.g.GaAs; $FT\{1/f\} = Step(x)=1$ $x>0$ all correlation scale i.e. self-similar noise characteristics
- CNT: $FT\{[1+(f/a)^2]^{-1}=\exp(-|x|/a)$ where $a=1.41A^o$



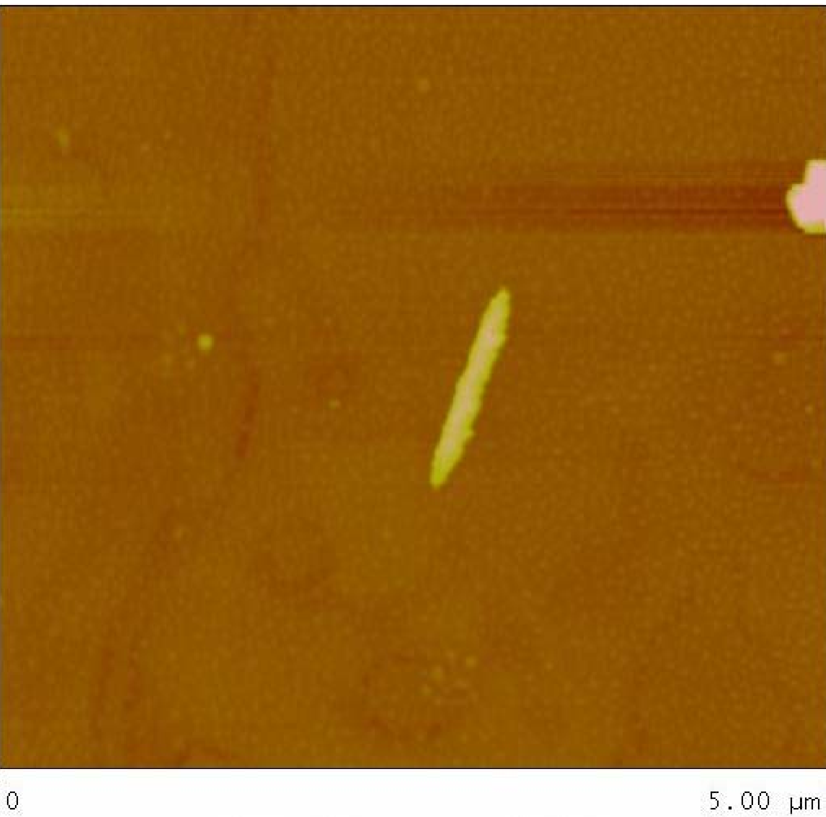
The picture shows a carbon nano tube (CNT) based IR detector array. Each pixel of the IR detector array consists of a multi-wall CNT with a proper tuned bandgap for detection of selected spectrum of the infra red.

Nanolithograph

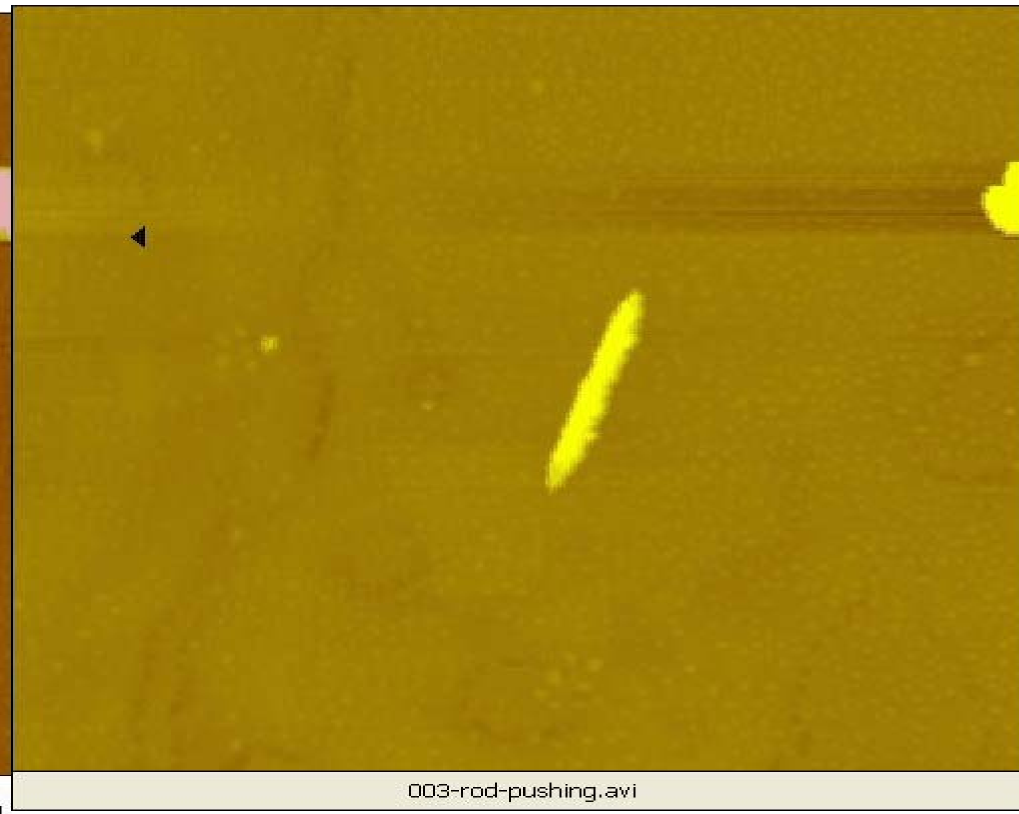


Nanoassembly Experiment

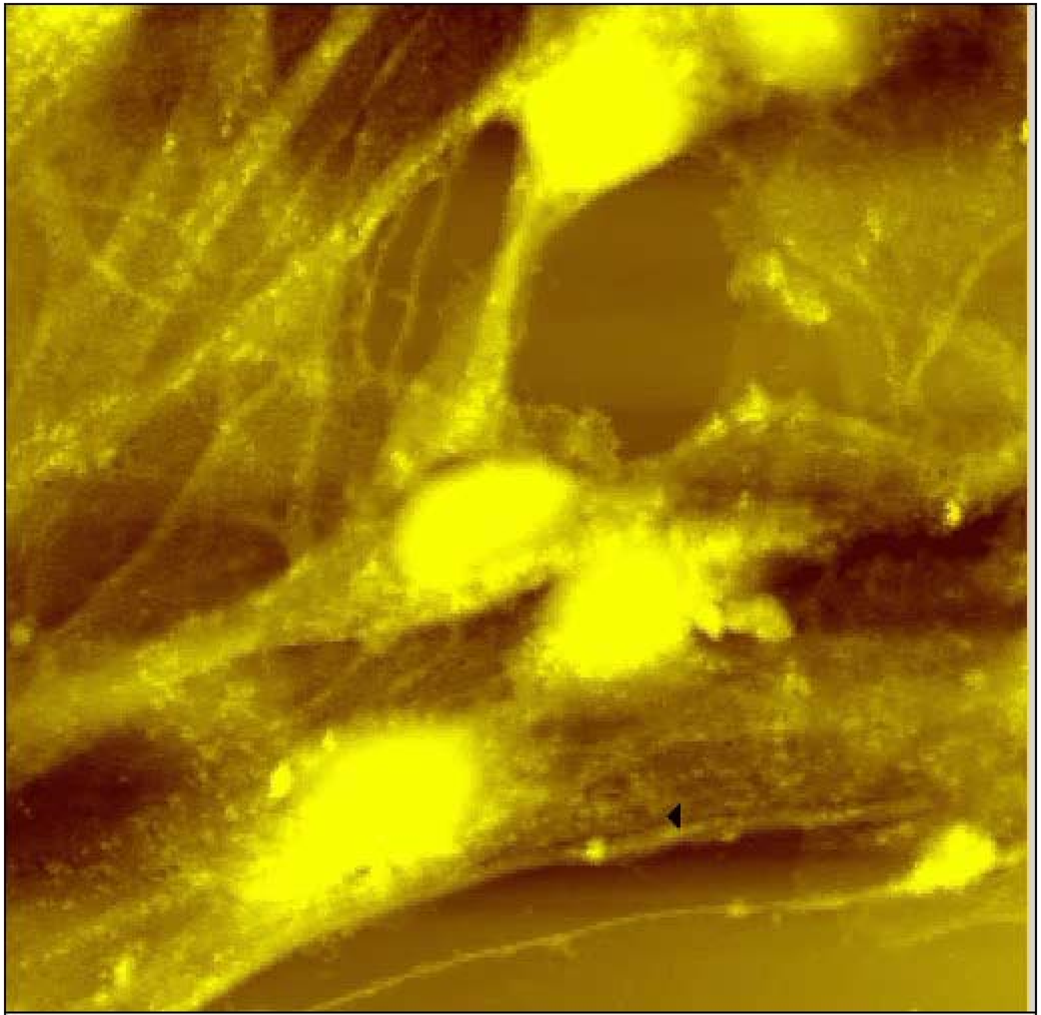
- Creating a fixture and then pushing a 100nm silver nanowire into the fixture (scanning size 5um)



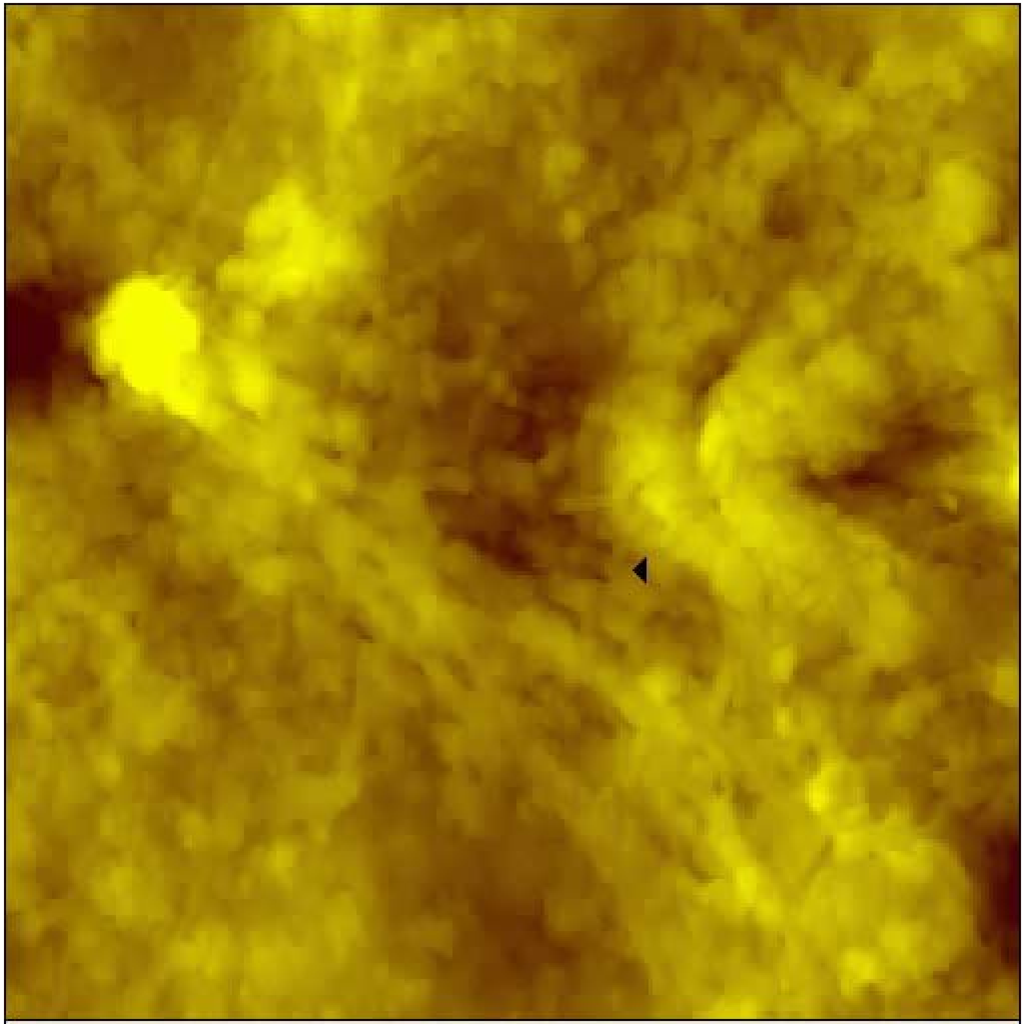
AFM image

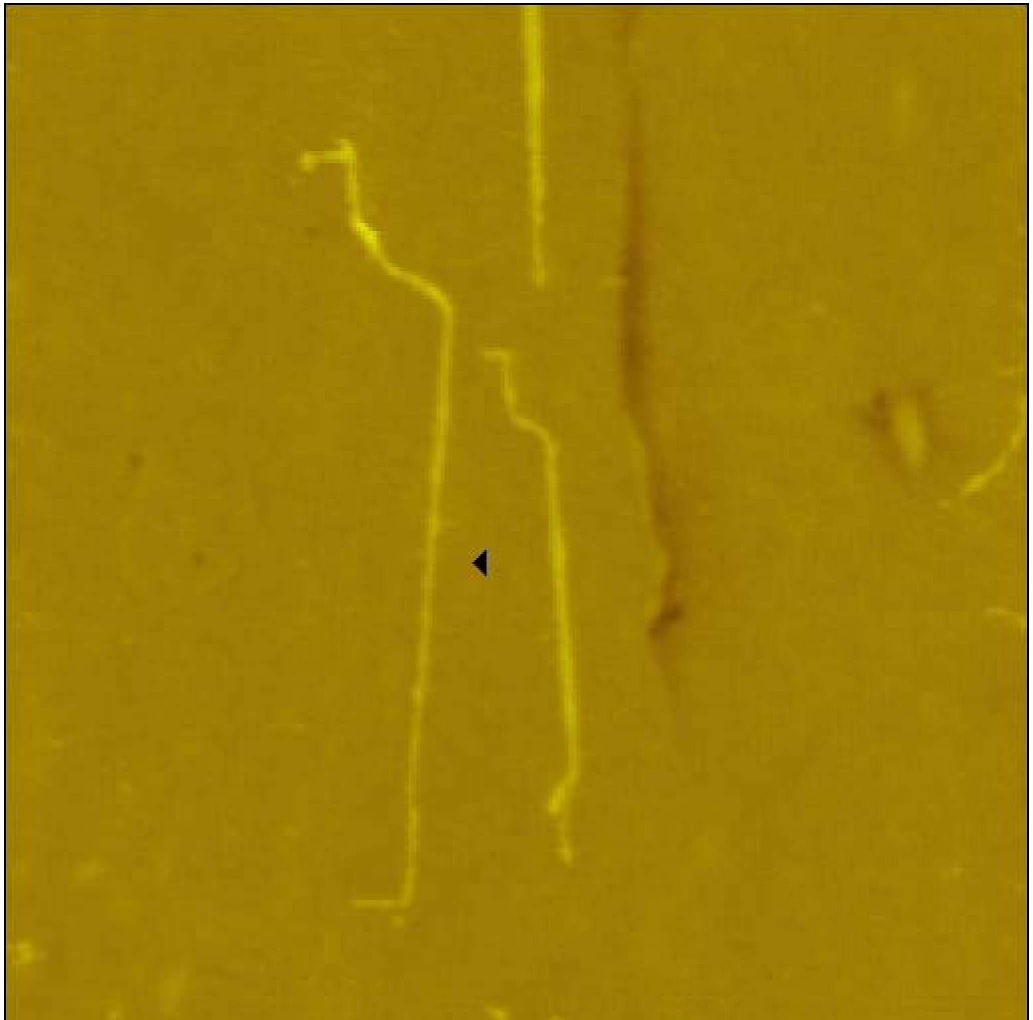


Real-time visual display



005-neuron-cutting.avi

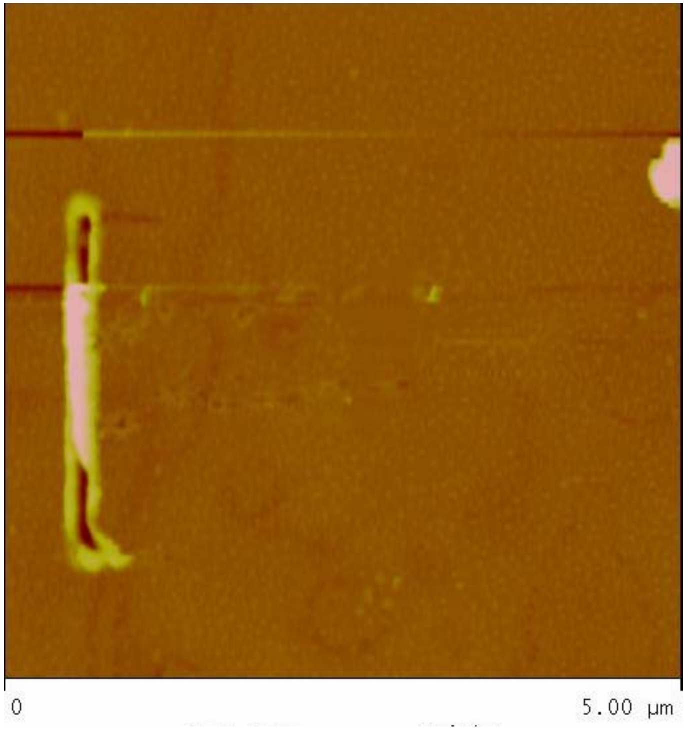

006-neuron-digging.avi



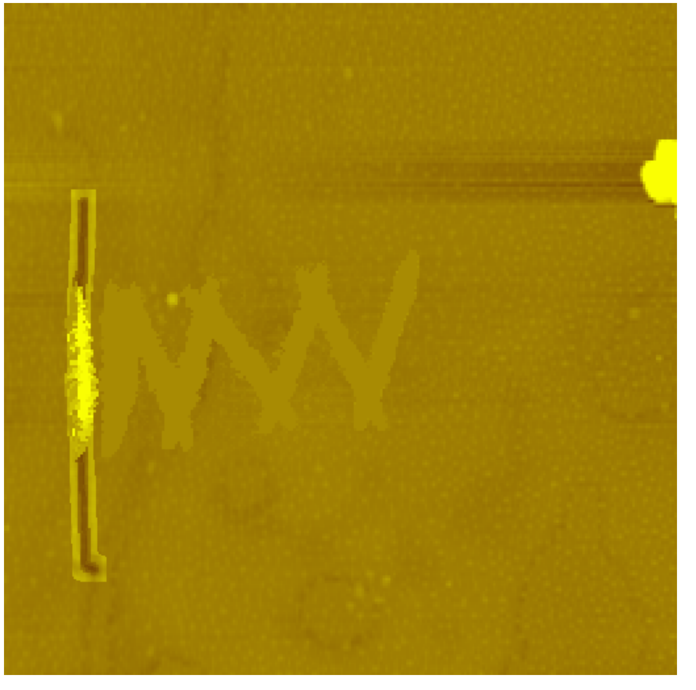
007-DNA-pushing.avi

Nanoassembly Experiment

- Creating a fixture and then pushing a 100nm silver nanowire into the fixture (scanning size 5um)



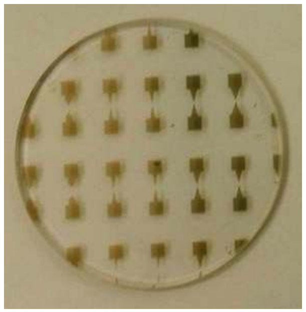
AFM image

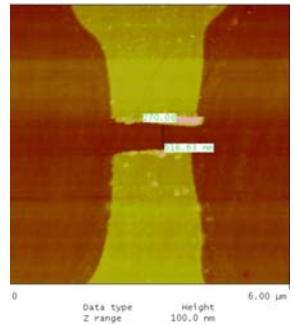


Real-time visual display

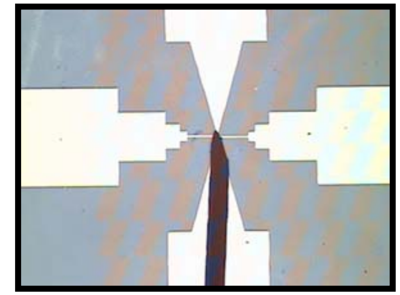
Fabrication Process

Substrate Fabrication

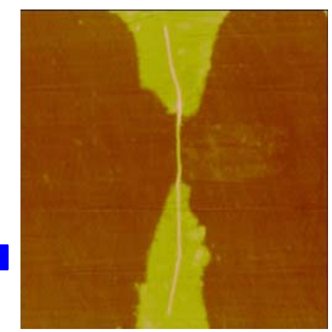




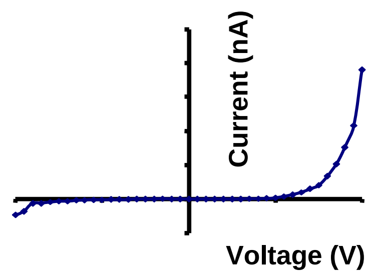
Nano lithography



CNT Deposition



CNT Assembly



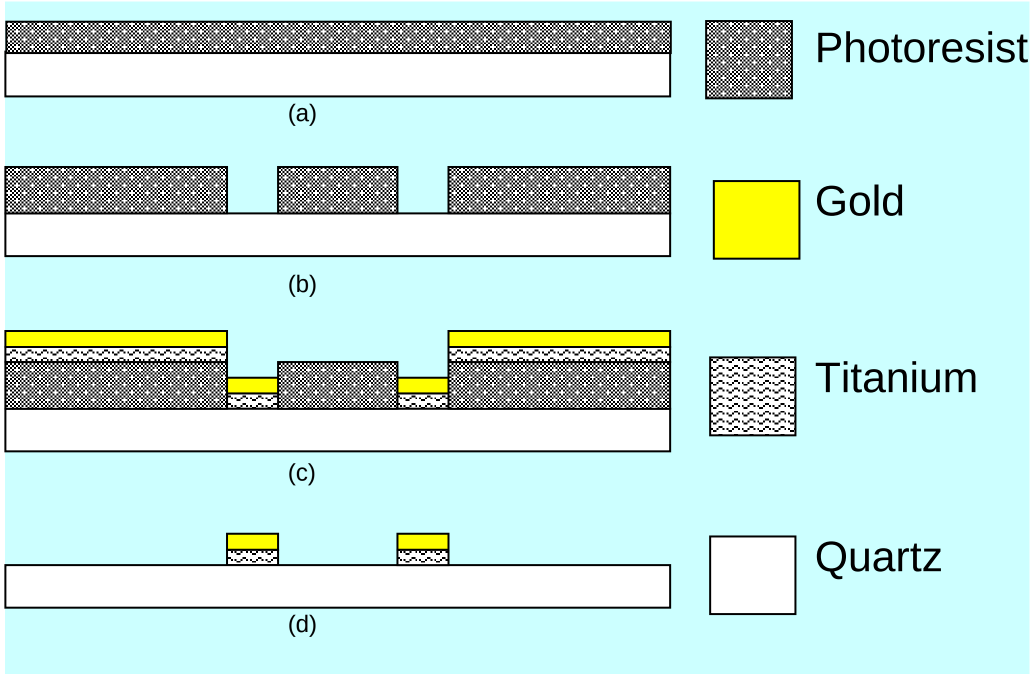
Band Gap Tuning

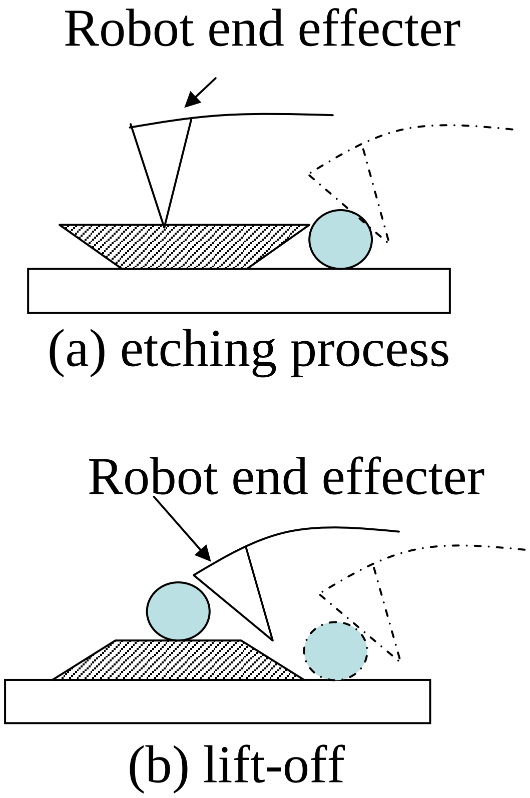
Chip Packaging

Final Testing

Substrate Fabrication

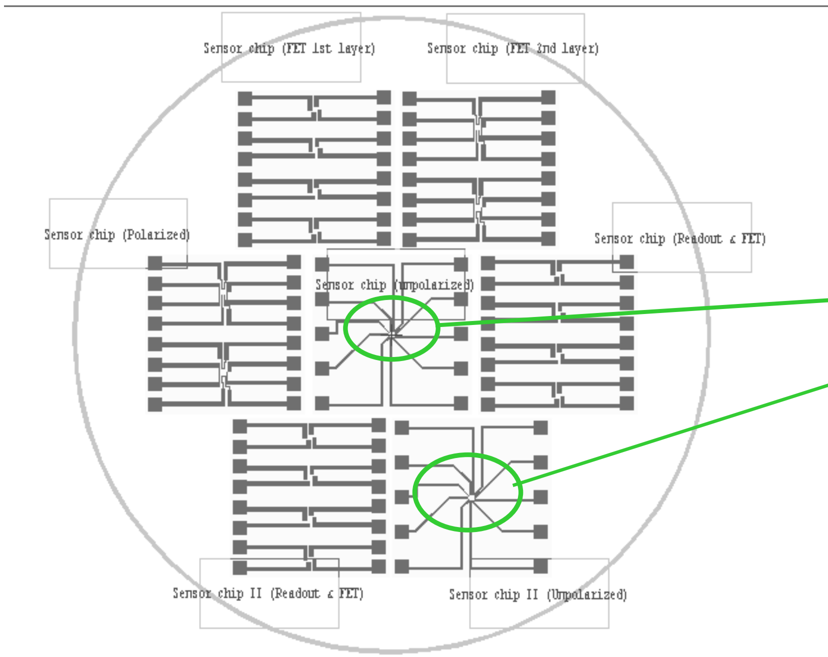
The electrode patterns are made from a lift-off process



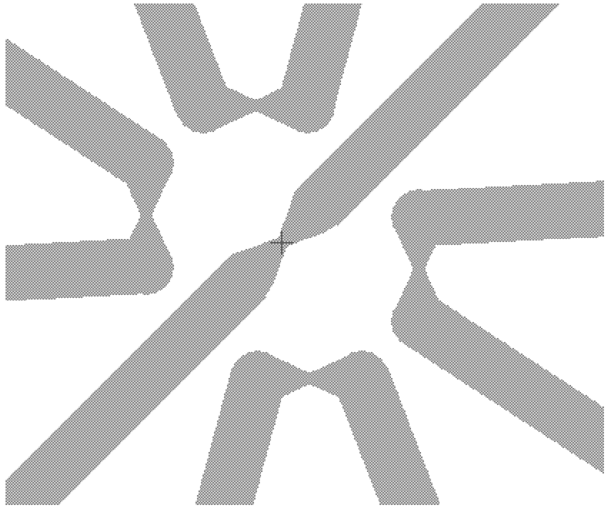


Mask Design and Fabrication

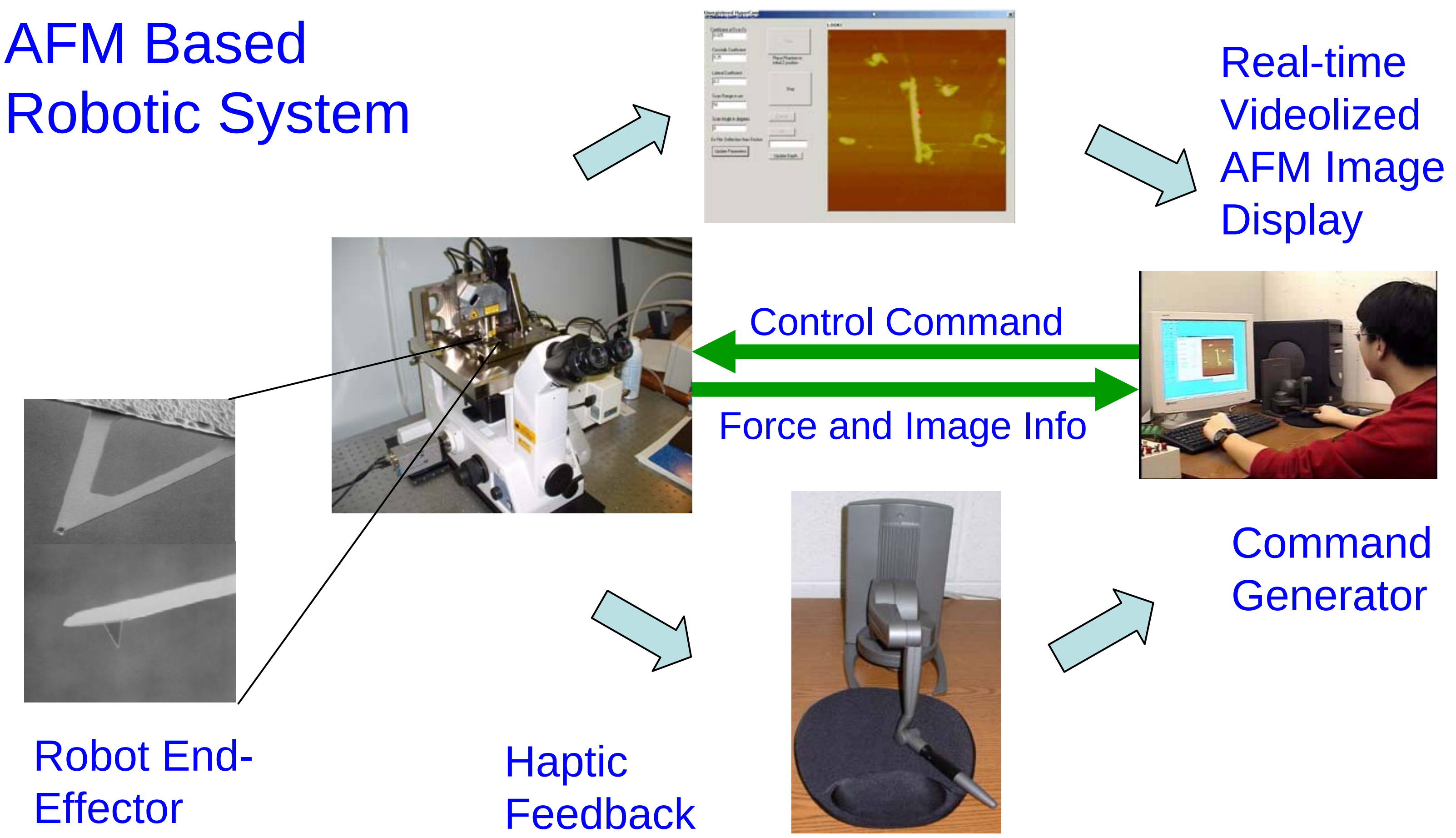
Unpolarized single pixel, which consists of five sub-pixel, is designed. The signal of the unpolarized single pixel is irrelated to the incident direction of the infrared.



unpolarized single pixel

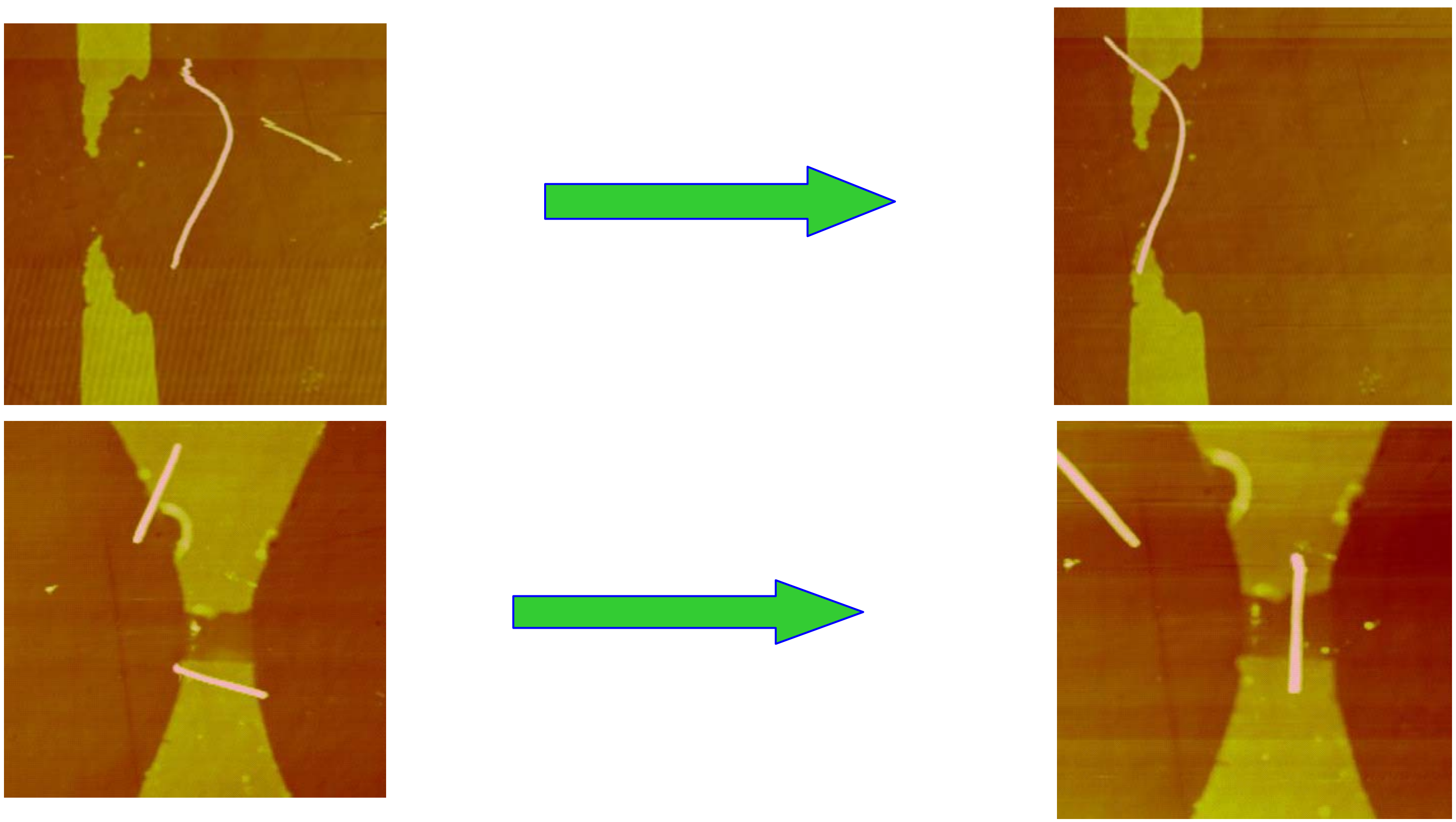


Fabrication and Assembly by Nano Robot



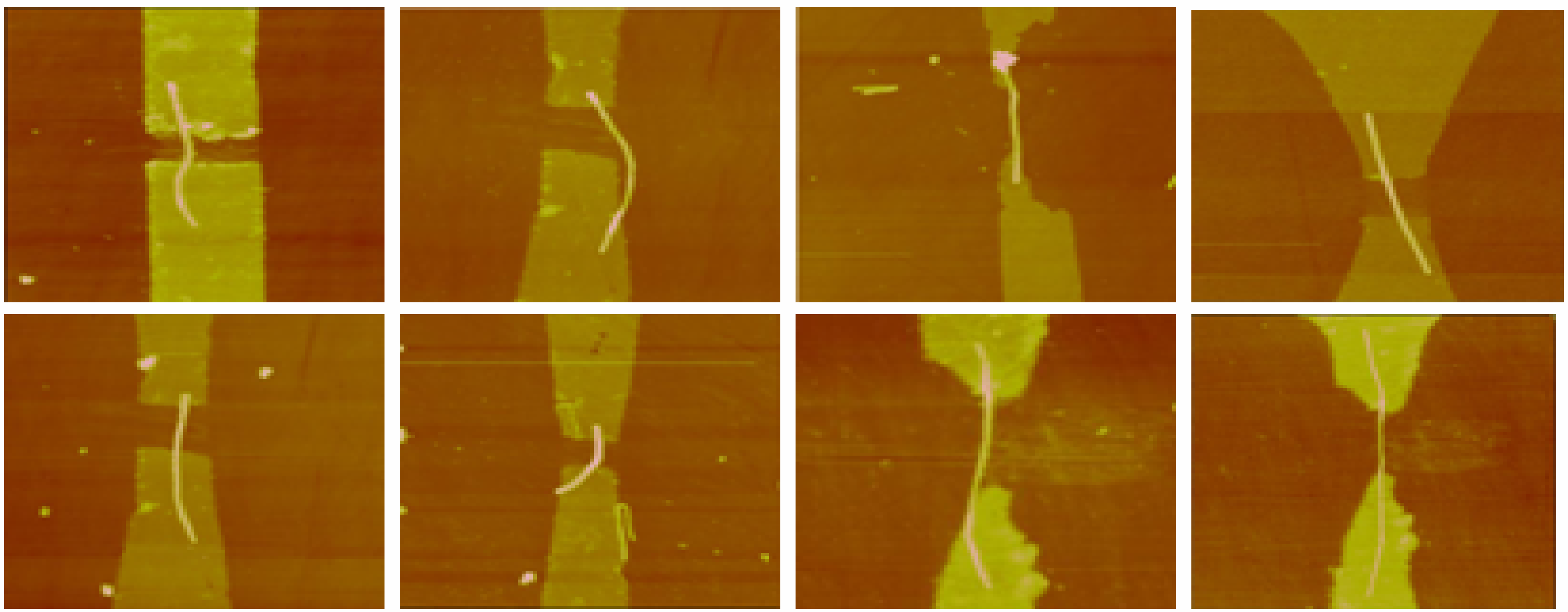
Placement of CNTs between Electrodes

The placement of a CNT between electrodes can be easily achieved using the AFM based nano robot



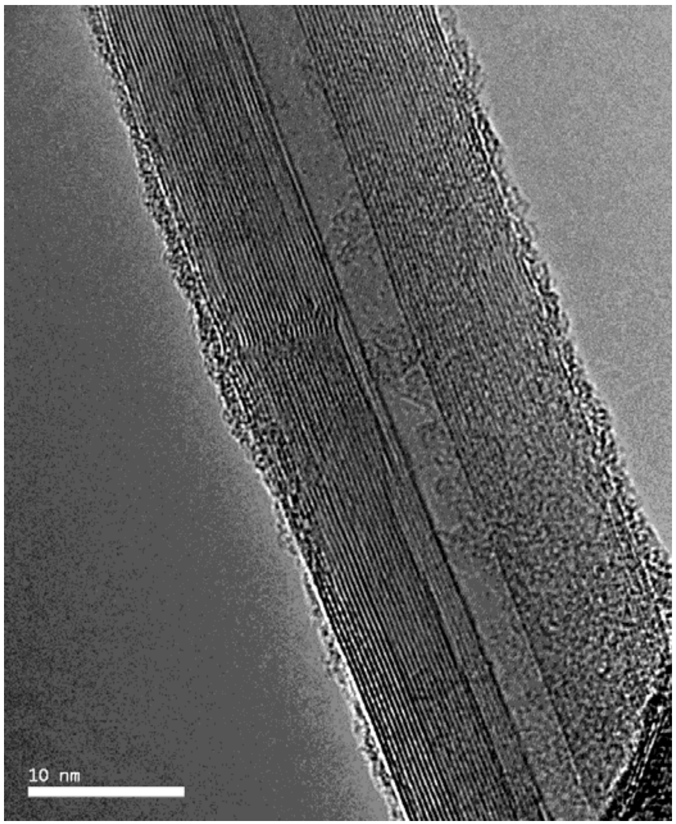
CNTs between Electrodes

- Assembled CNT based detectors

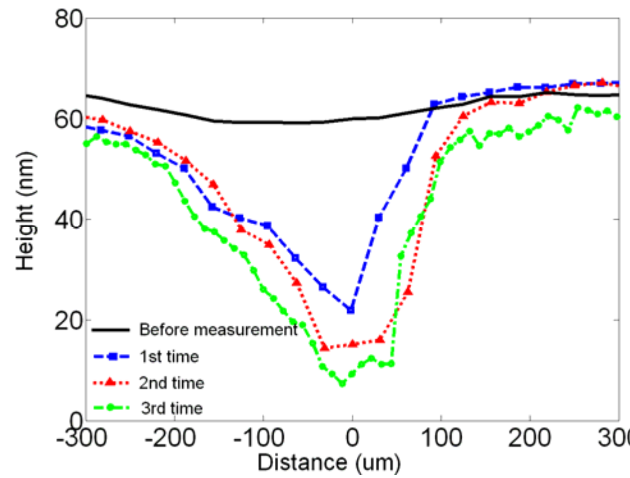


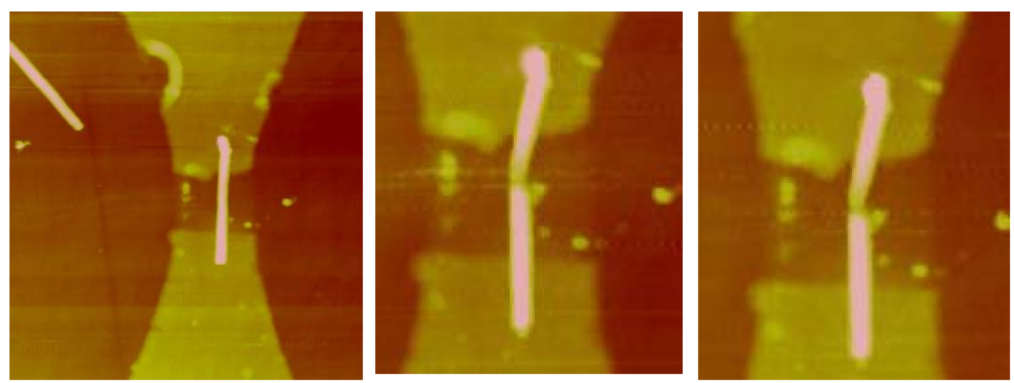
CNT Band Gap Tuning by Breakdown

TEM image of MWCNT

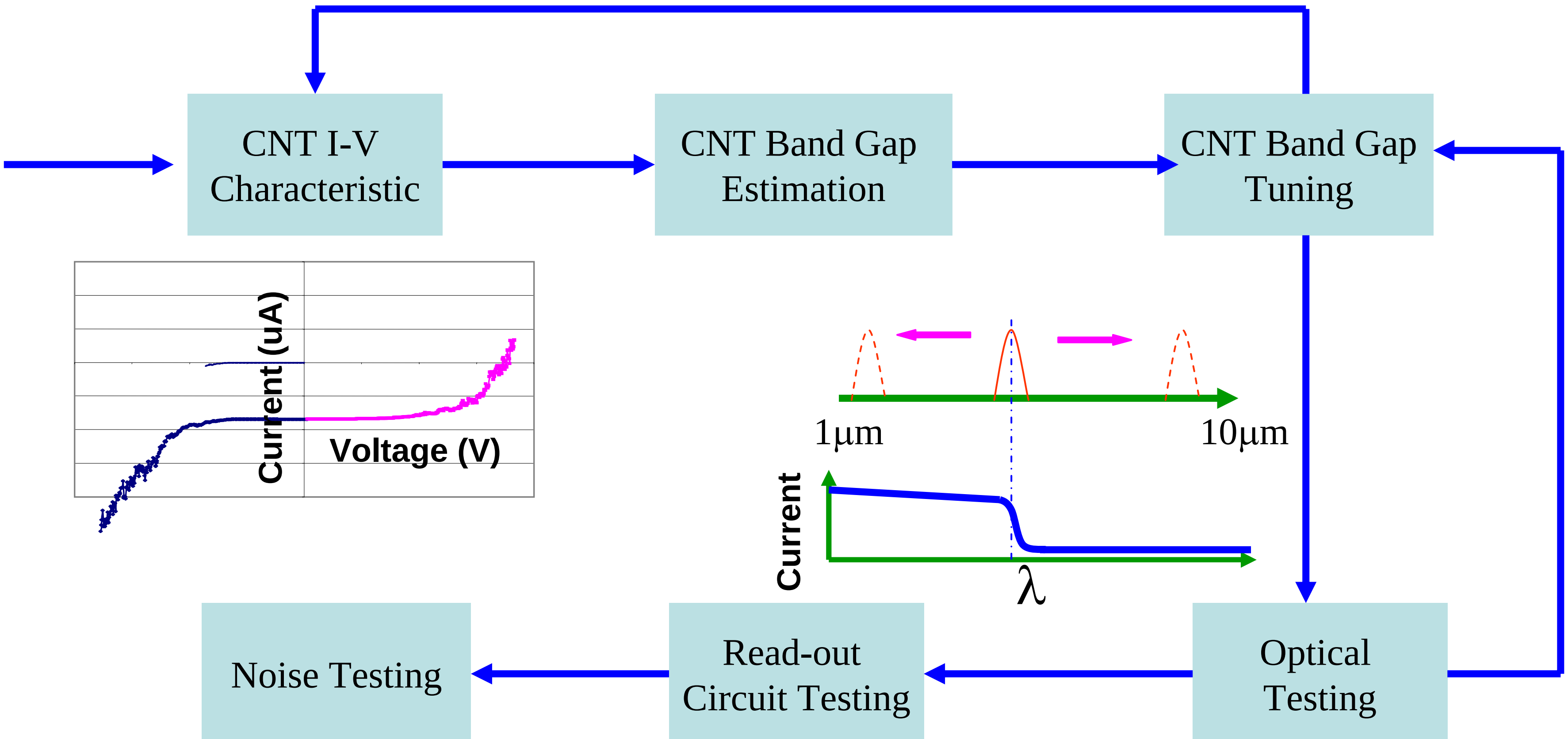


Topography of MWCNT



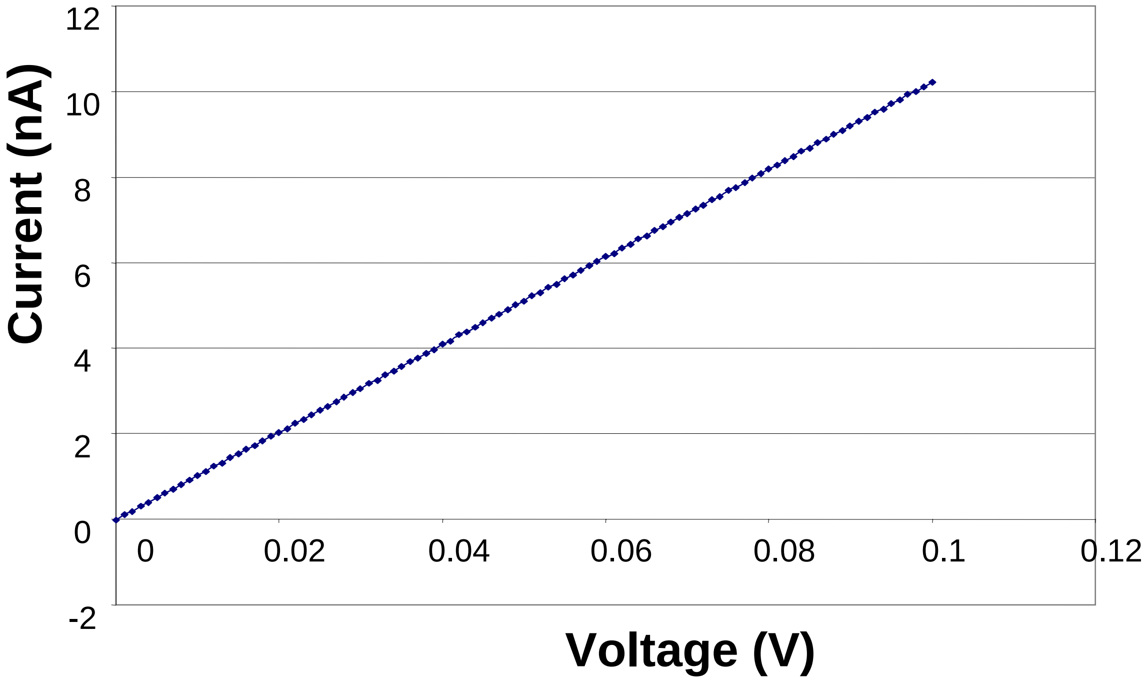


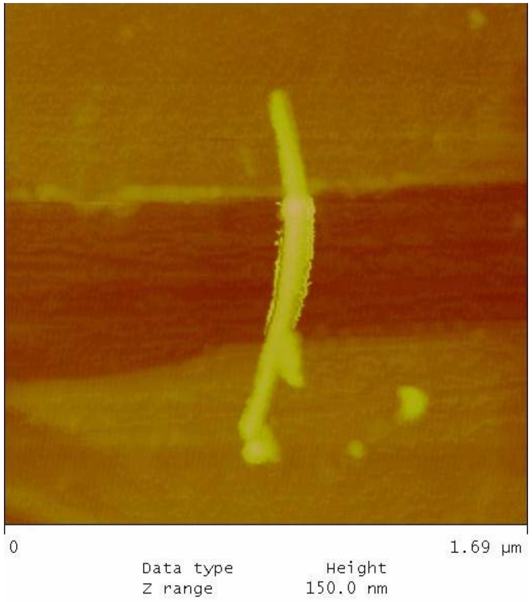
Testing and Results



I-V Characteristic of a CNT

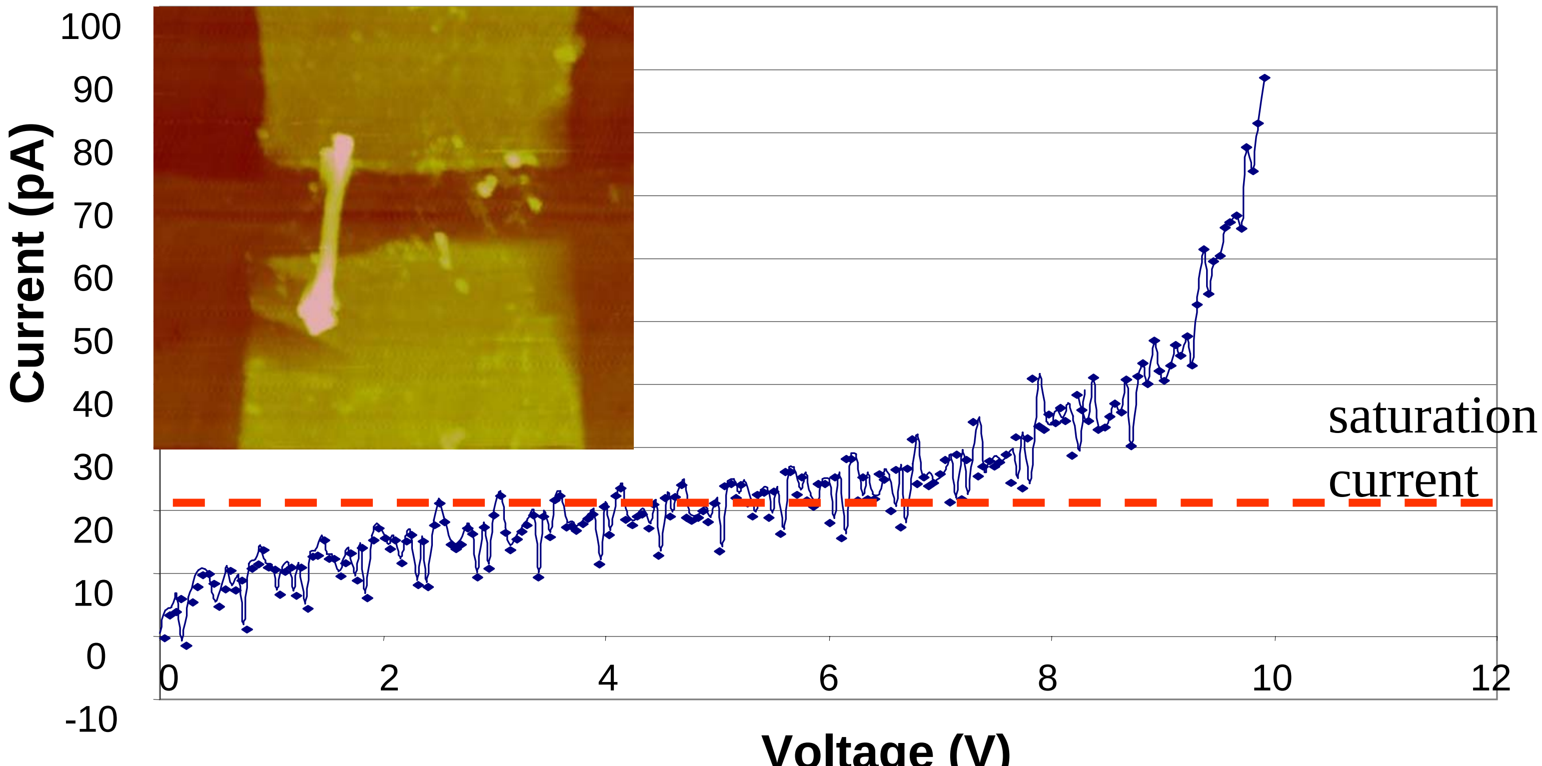
Metallic behavior of CNT, the resistance of CNT is very small. The figure shows the CNT in serial connection with 10M Ohm resistor





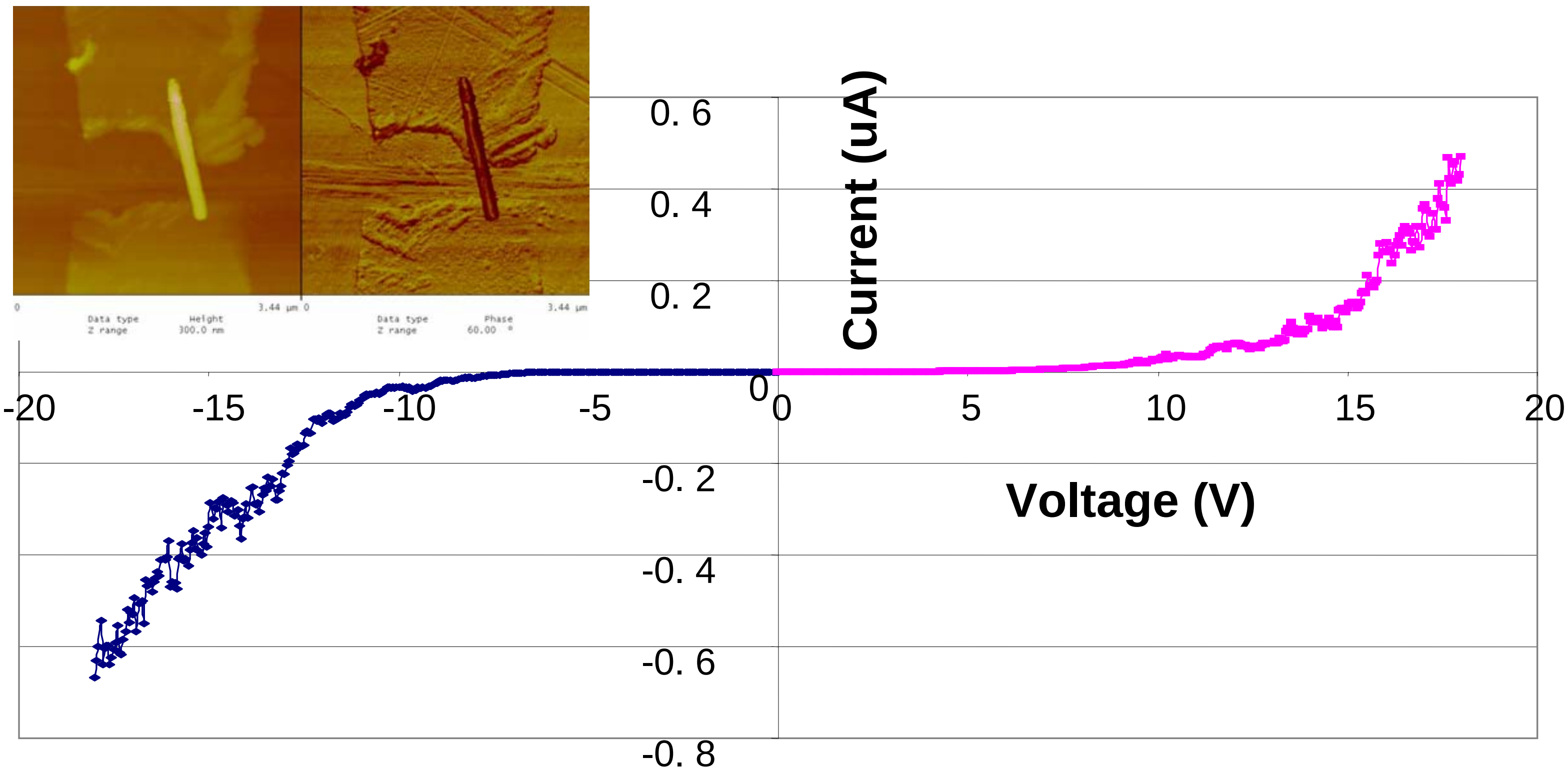
I-V Characteristic of a CNT

Semi-conducting behavior of CNT. The figure shows the CNT in serial connection with 10M Ohm resistor



I-V Characteristic of CNT

Semi-conducting behavior of CNT. The figure shows the CNT in serial connection with 10M Ohm resistor. (-18V~18V)

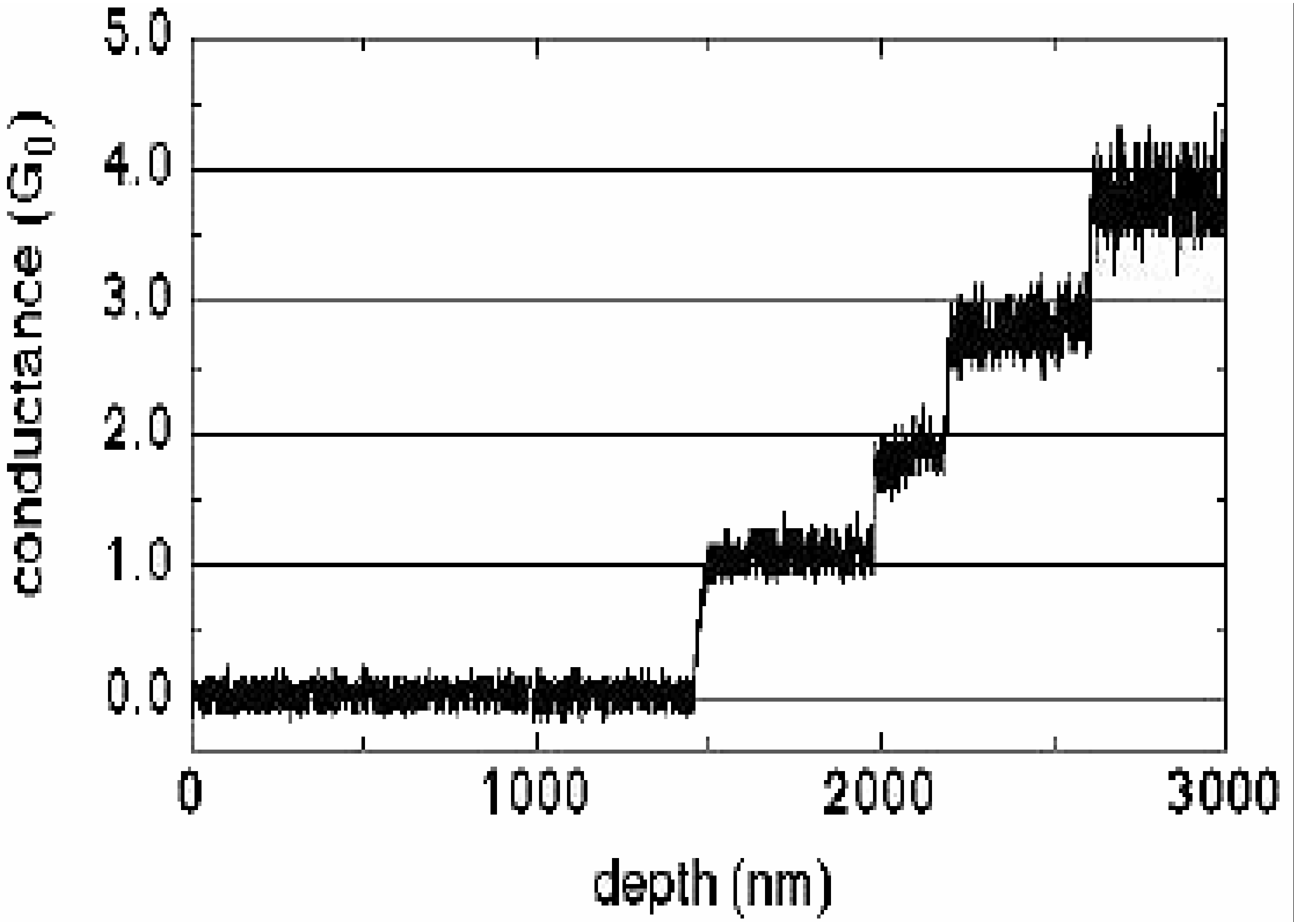


Smart Vision Sensors: Rods & Cons

- Massive parallel & densely uniformly packed fovea 6.3 Millions cons for color perception
- Distribution of 150 Millions rods are non-uniformly, polar-exponentially packed along radial direction
- Scale Invariant Architecture-Algorithm (Archirithm or Algotecture): data X = exp (U), feature domain u' =log x/2= log x- log 2=U gracefully degradation
- Ultra sensitivity: How could Single Photon be Detected by Human Vision Sensor at dark night? Although Rhodopsin molecule convert efficiently photons to charges as signal, but the energy of a photon is not enough for detection. CNT may realize it.

1-D multi-walls CNT Electrical Transport in Armchair

- Ballistic quantum conductance
- Absence of backward scattering
- High maximum current density: 10^7~10^13 A/cm^2

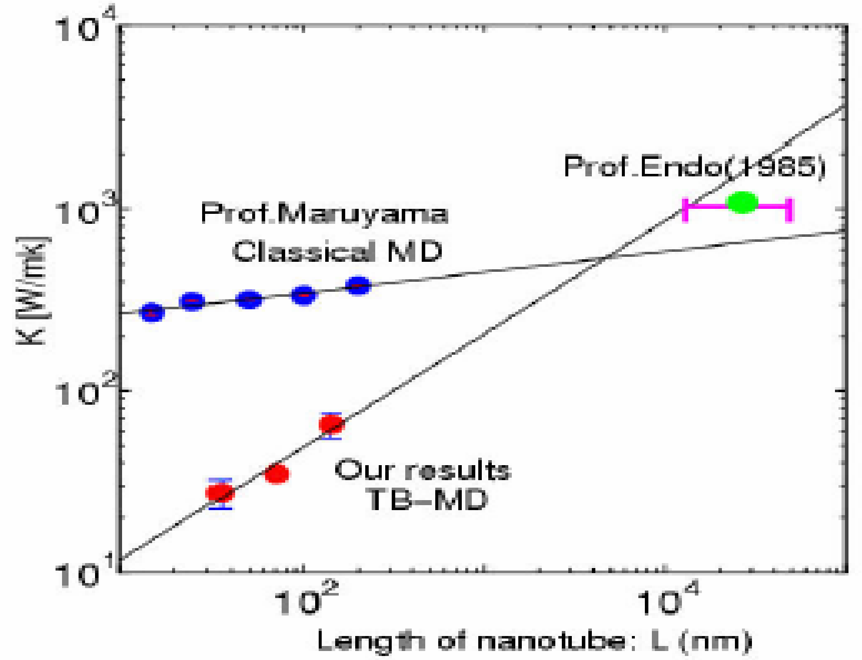


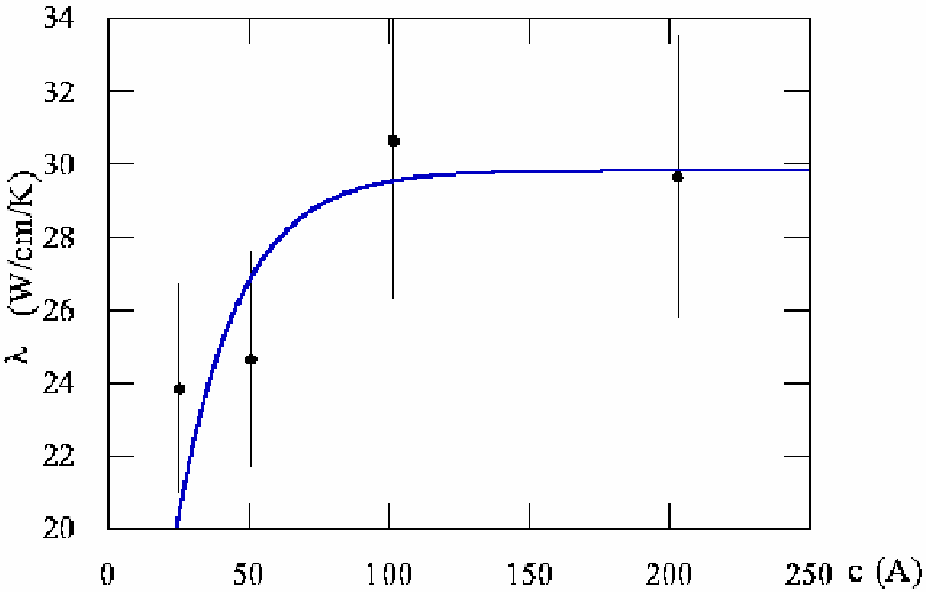
Above: A carbon nanotube is a quantum conductor. The conductance rises by 1 G_0 as the depth increases sufficently. G0= 2e2/h

Stefan Frank et al., Science 280 1744 (1998)

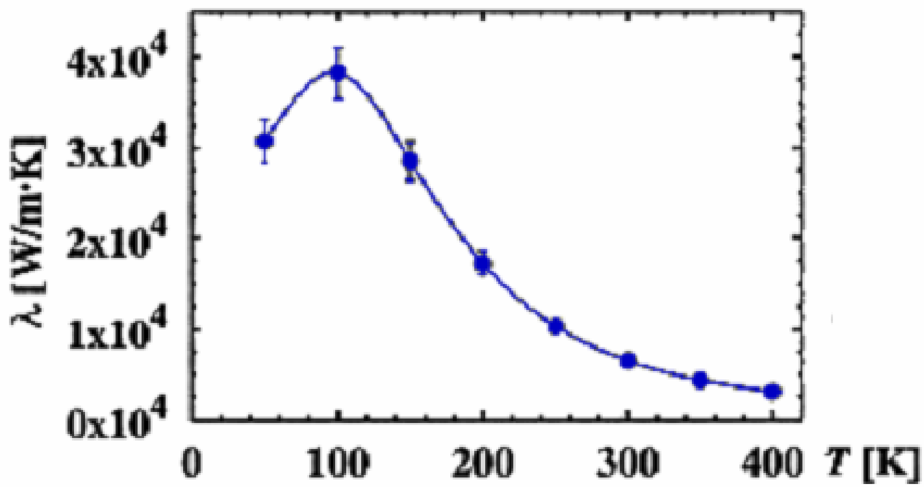
Thermal Transport in CNT

- Temperature dependency
- Length dependency
- Long-wave phonon: twiston





The thermal conductivity as a function of current. by Jianwei Che



Thermal Conductivity as a function of Temperature
(S. Berber, et al 84, 4613(2000))