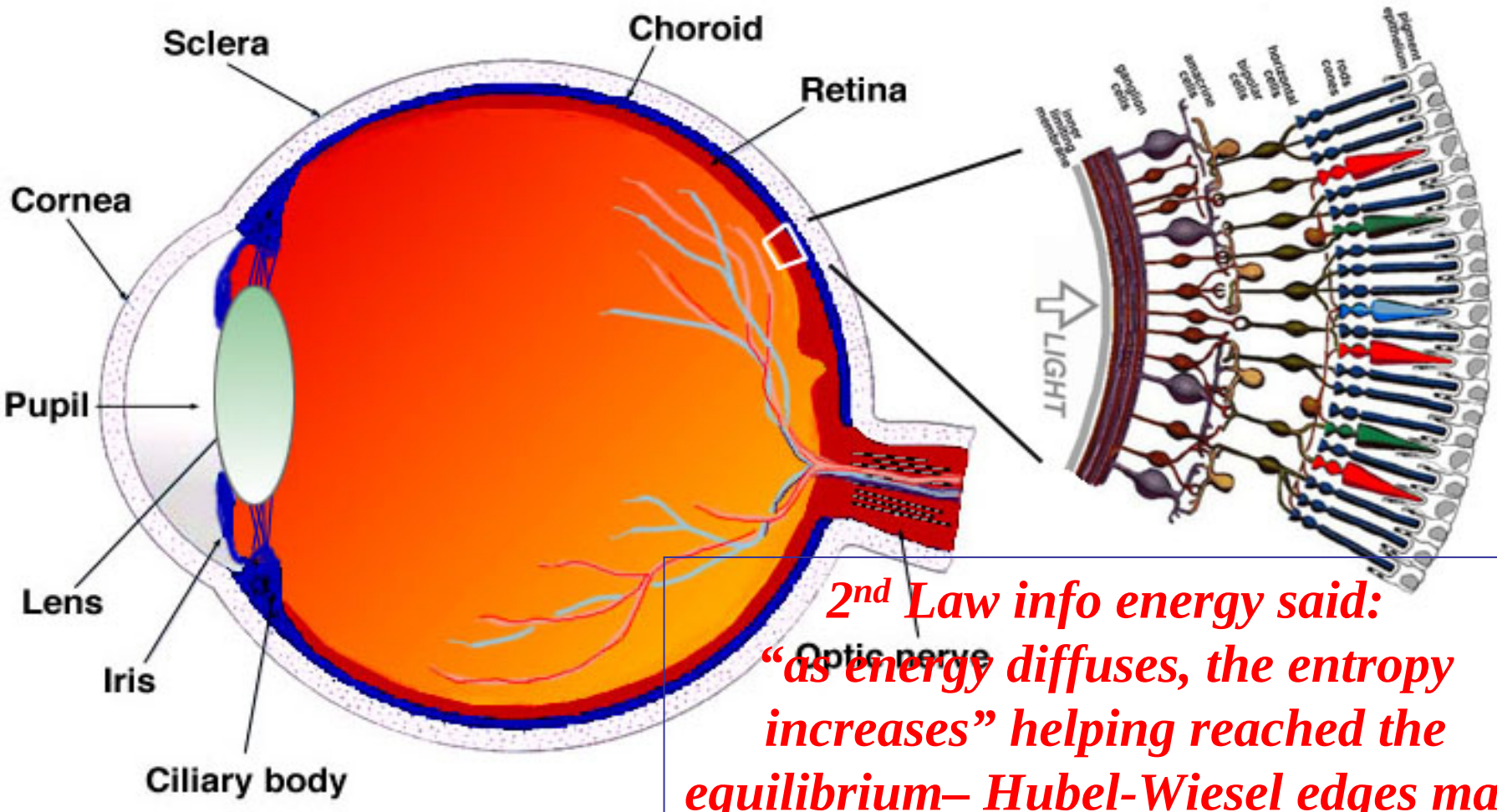
3. Nano Camera Fabrication Technology

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 ™” replacing traditional contact thermometers based on either thermal coupler or Mercury thermometer

Nano-photonics must learn from our eyes?

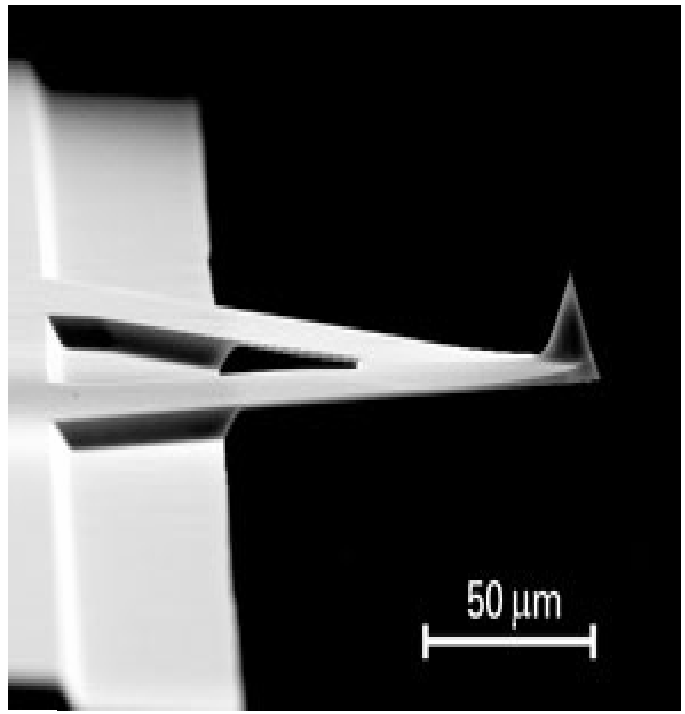
156 millions rods-cones excitations must decay to save energy and make room for further excitations. Pseudo-1-D cone suffers less noise, enjoy single photon detection without Liquid Nitrogen coolant =Nano-photonics need CAD NanoRobot manipulator, from 1 meter to 10^{-9} meter!

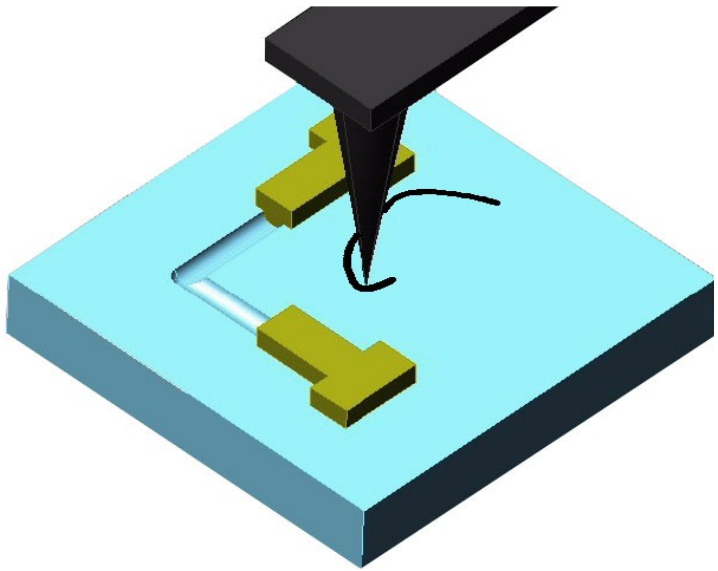


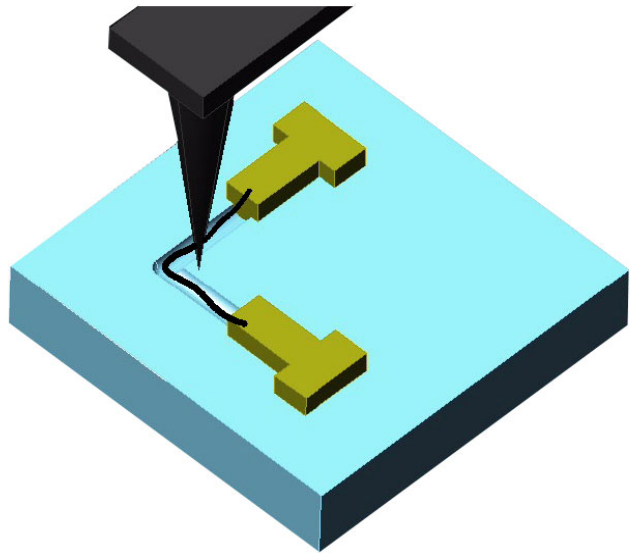
2nd Law info energy said: "as energy diffuses, the entropy increases" helping reached the equilibrium– Hubel-Wiesel edges map

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:

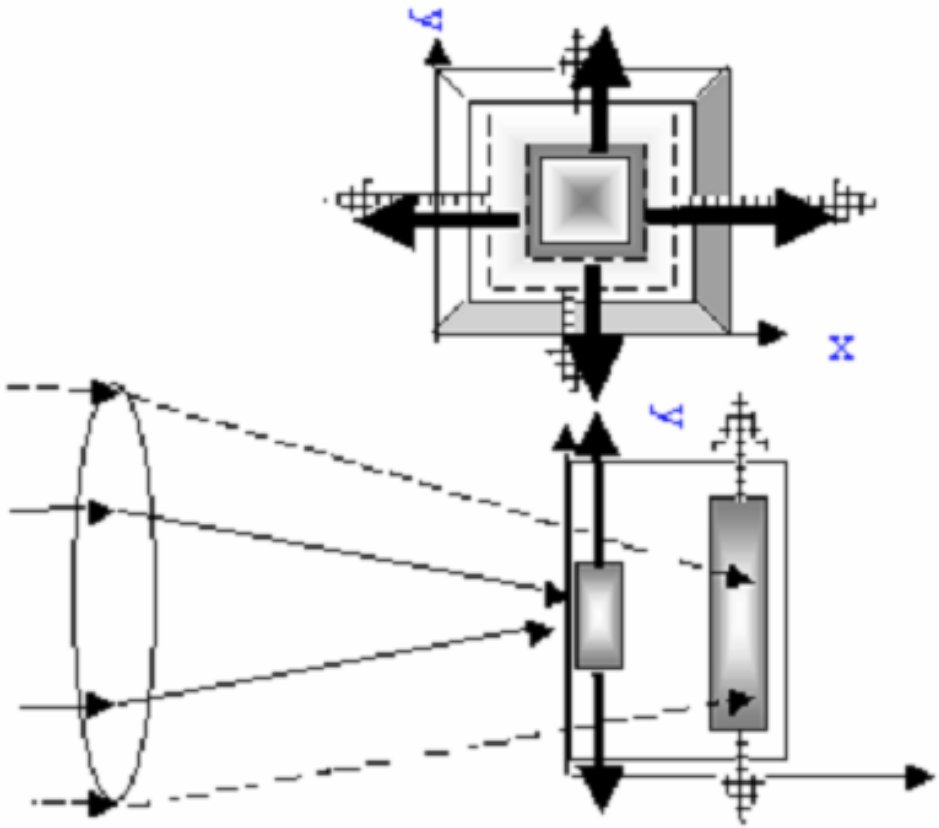
nano-robot

(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

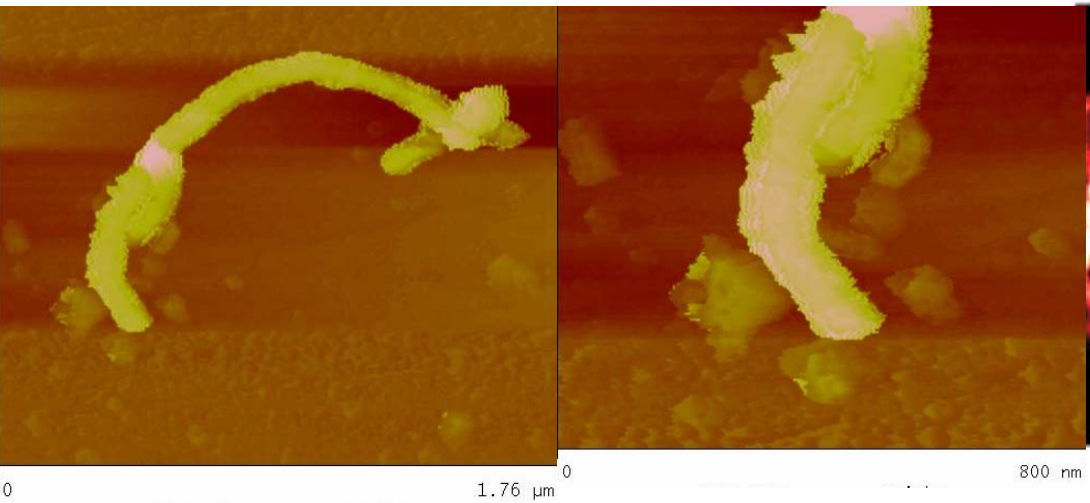
*Szu et al. Patent Disclosure 2004

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

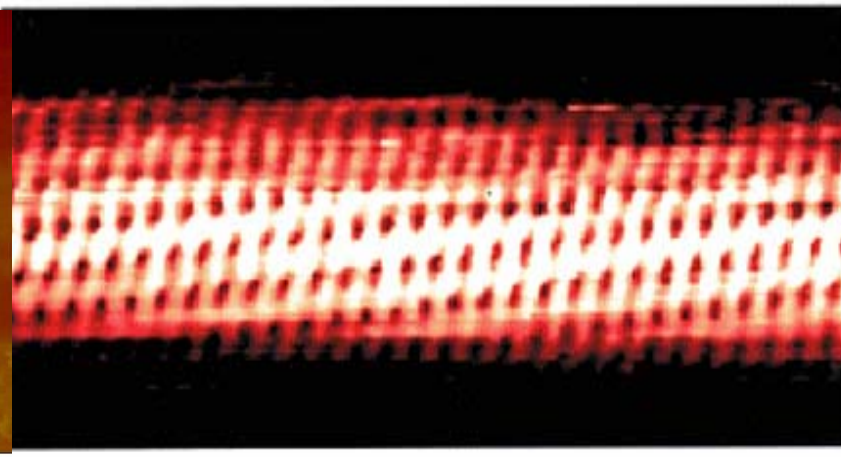
- Navy Patent 2004 unsupervised fusion by Szu et.al. can provide unbiased feature extraction.
- Un-cooled 2 Color Infrared Camera under $1K can provide mini-UAV new capability and dual usage for family spectrum thermometer for sport medicine and early tumor diagnoses.

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

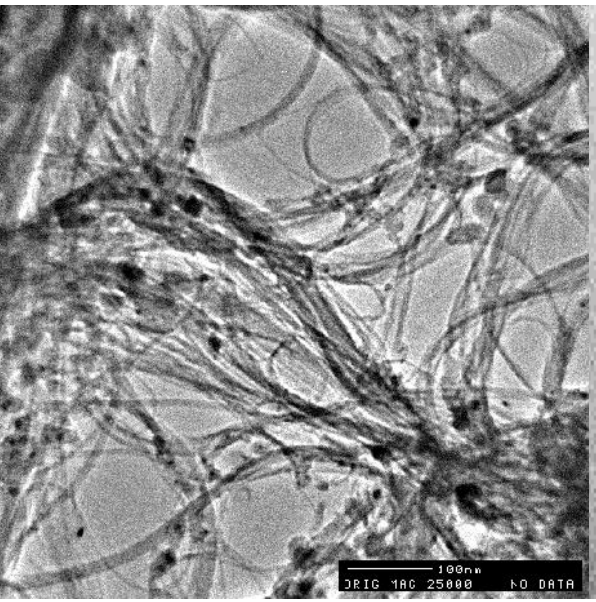
AFM image



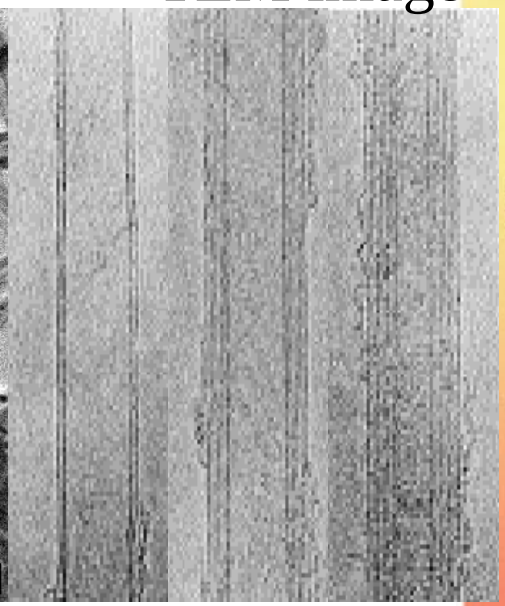
STM image of CNT



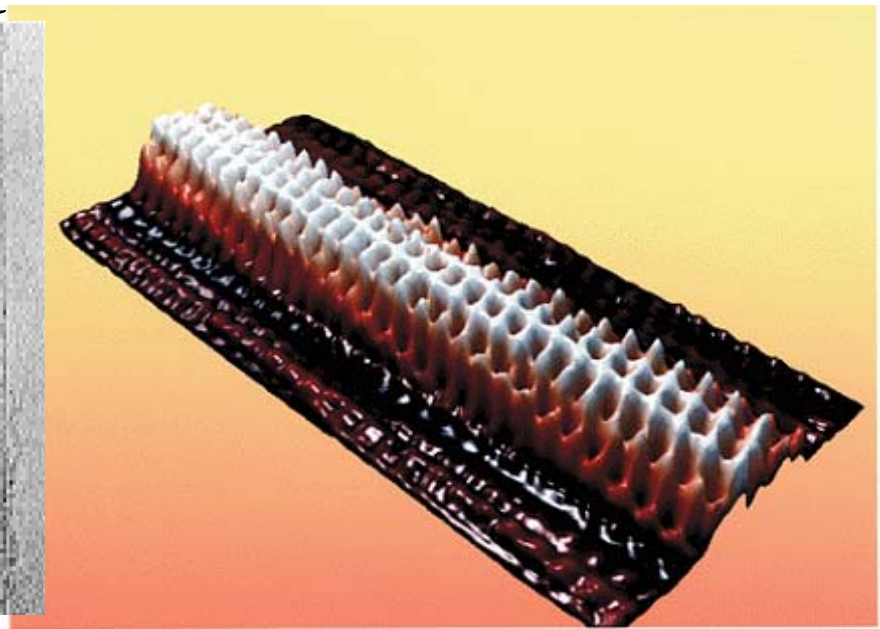
SEM image



TEM image



Cees Dekker, Delft Univ of Tech

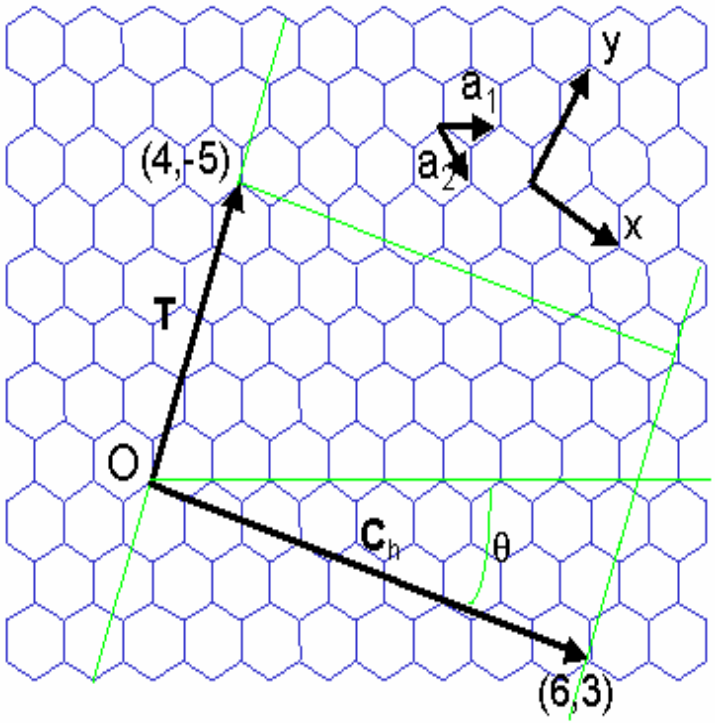


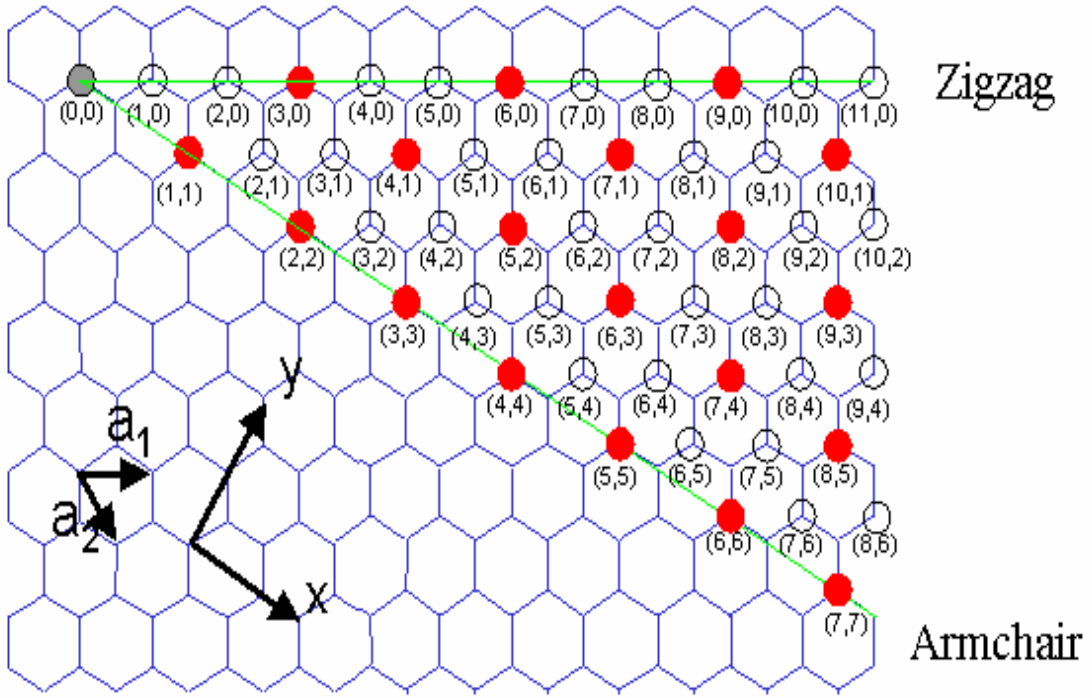
Why Nano technology CNT for double color Infrared Camera?

- 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

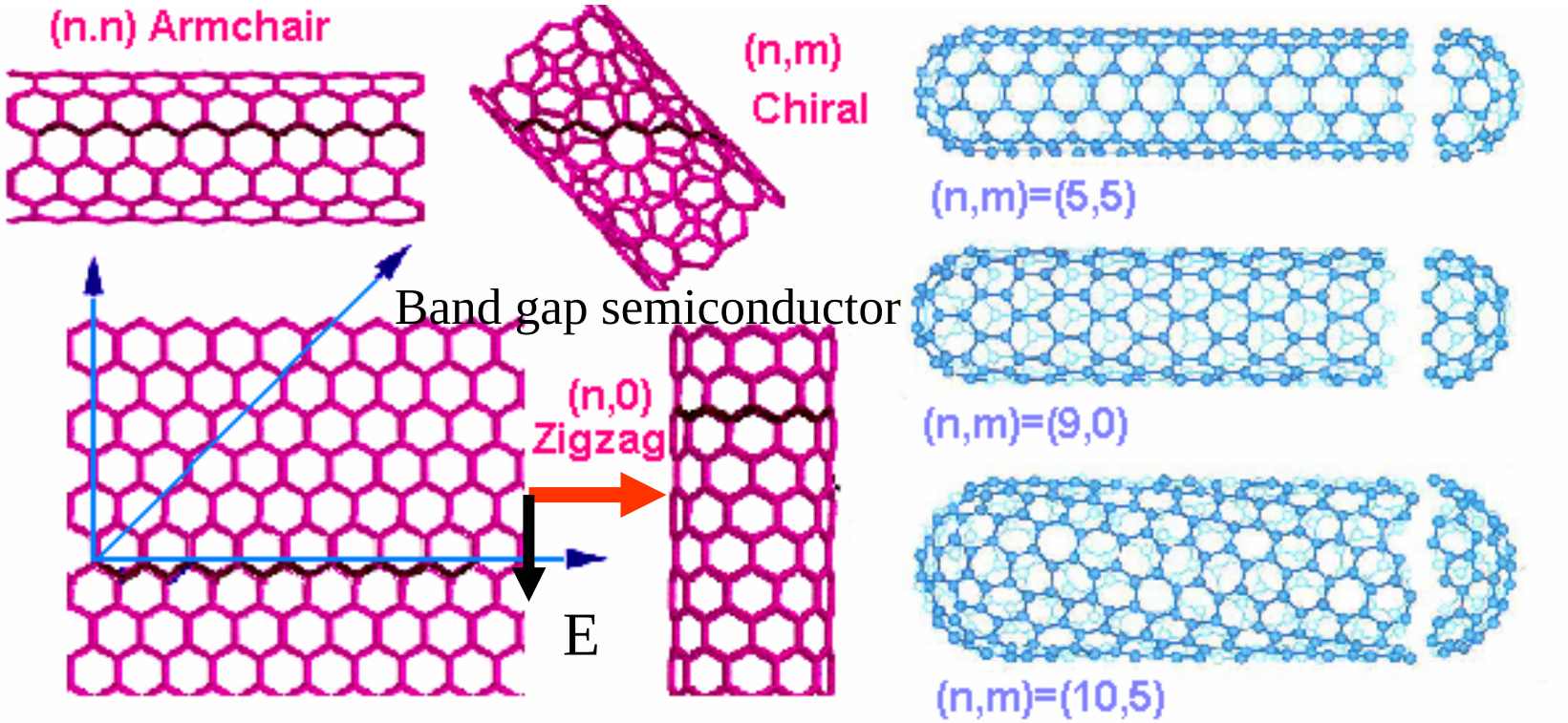
- Folding Chiral vector is defined as $C_h = n\vec{a}_1 + m\vec{a}_2$
- The translation vector T is perpendicular to the chiral vector
- (n,m) is the index of CNT





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

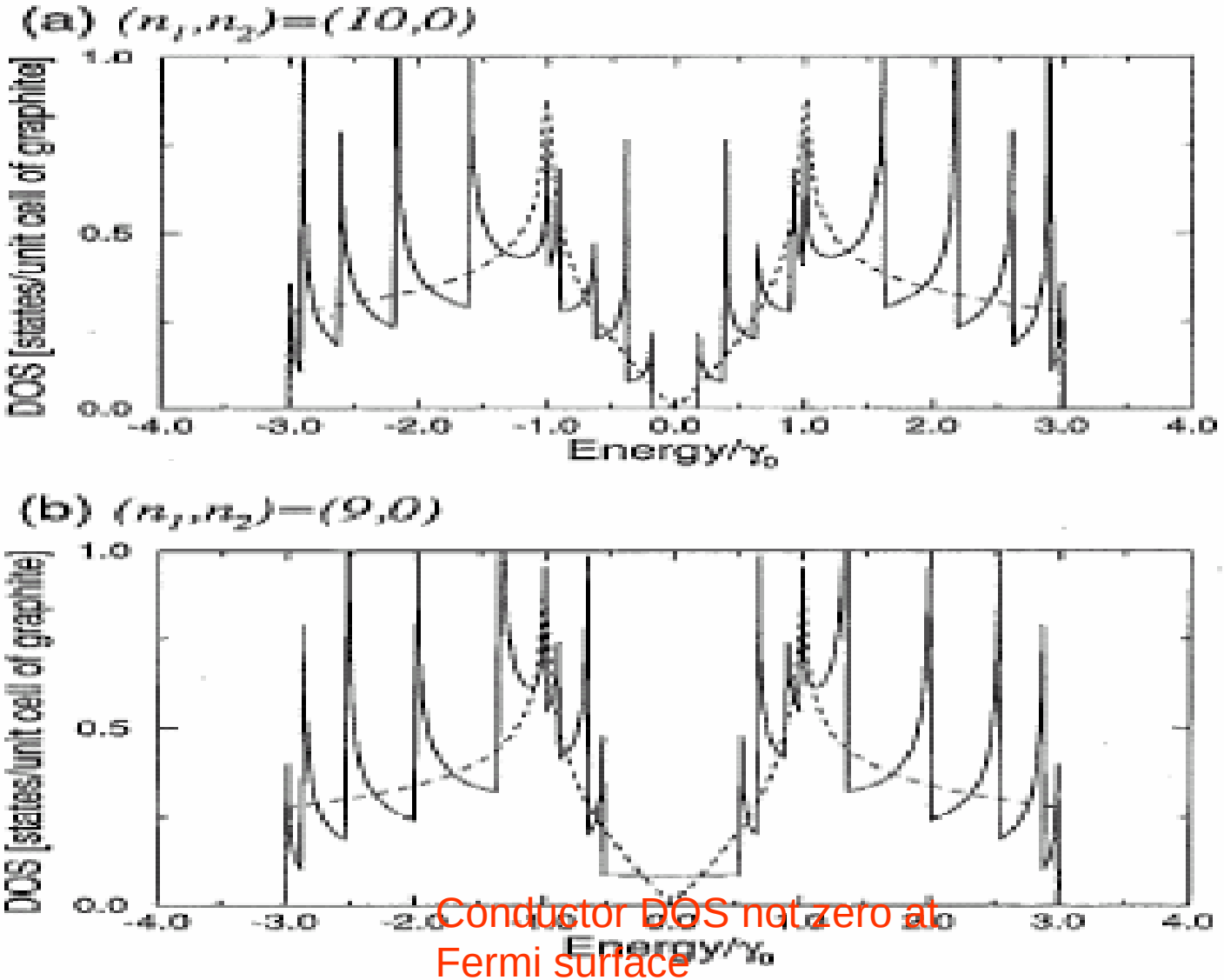
$$Ck = 2\pi \,\text{int}\, egers$$

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

$$n_1 = n_2$$

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

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

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

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

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

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

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

Structure Dependency of Bandgap

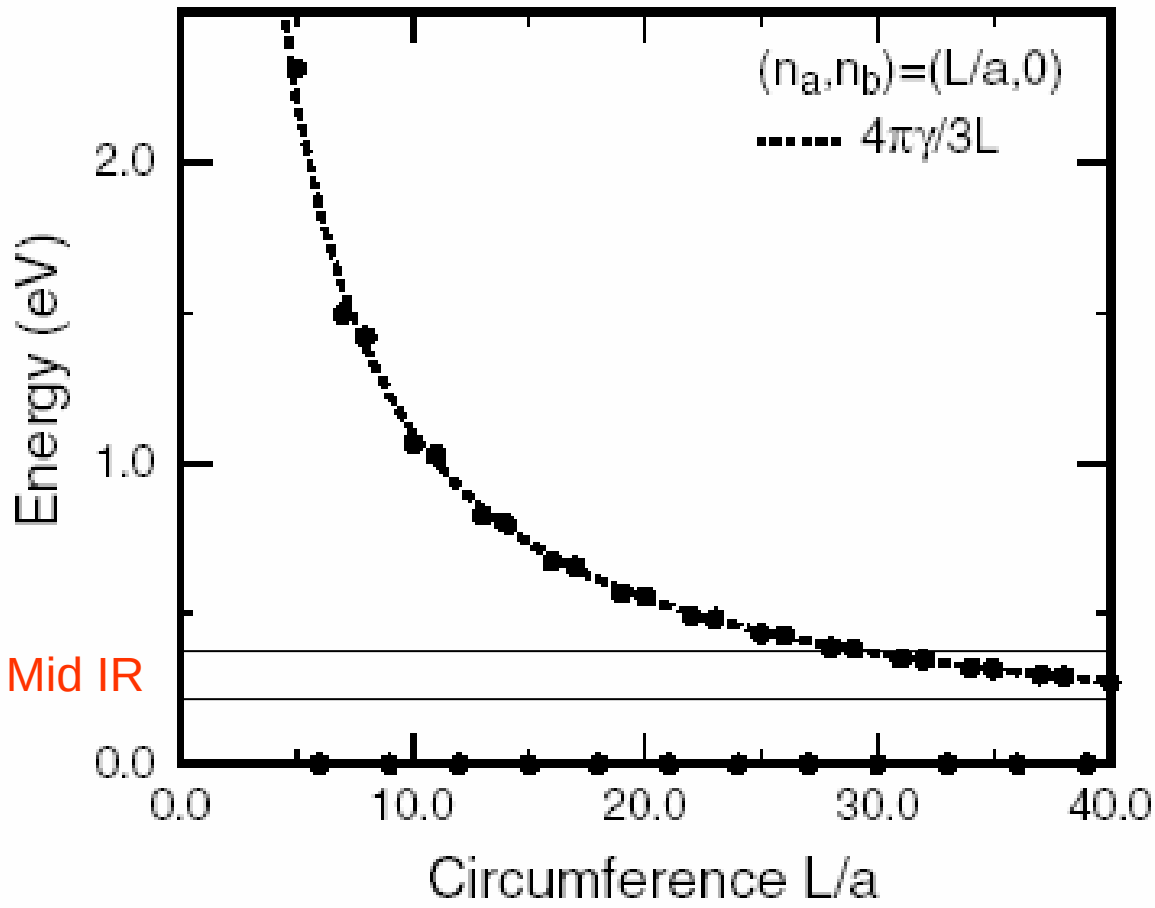
Mid IR 3 to 5 micrometer

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

- 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

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

$M_i \approx 2x10^{-23}$ 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

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

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

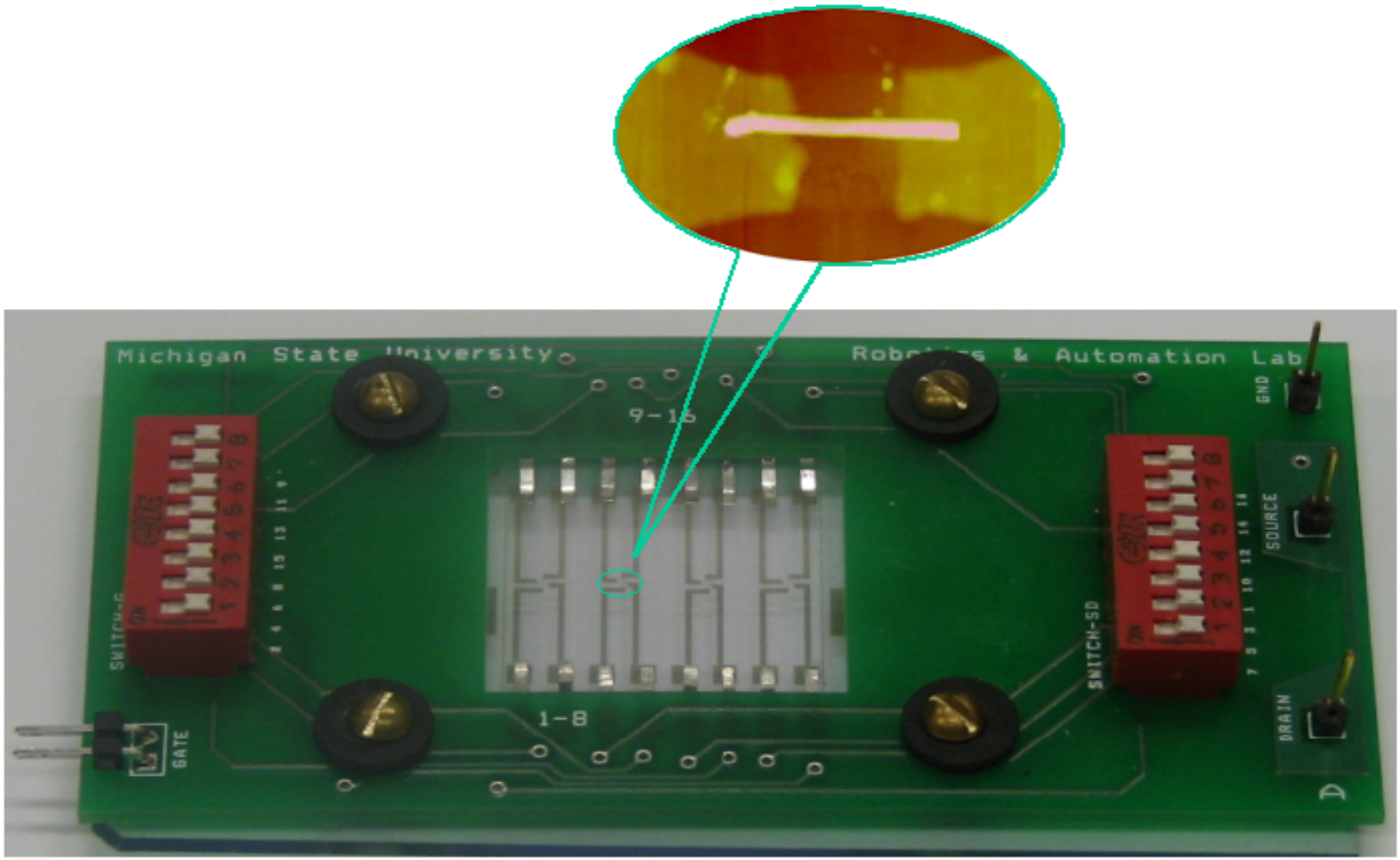
$$SNR_{room} = \frac{0.4 \Leftrightarrow 0.2}{0.01} = 40 \Leftrightarrow 20\ if\ 1-D\ (otherwise: 13 \Leftrightarrow 7\ for\ 3-D)$$

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

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

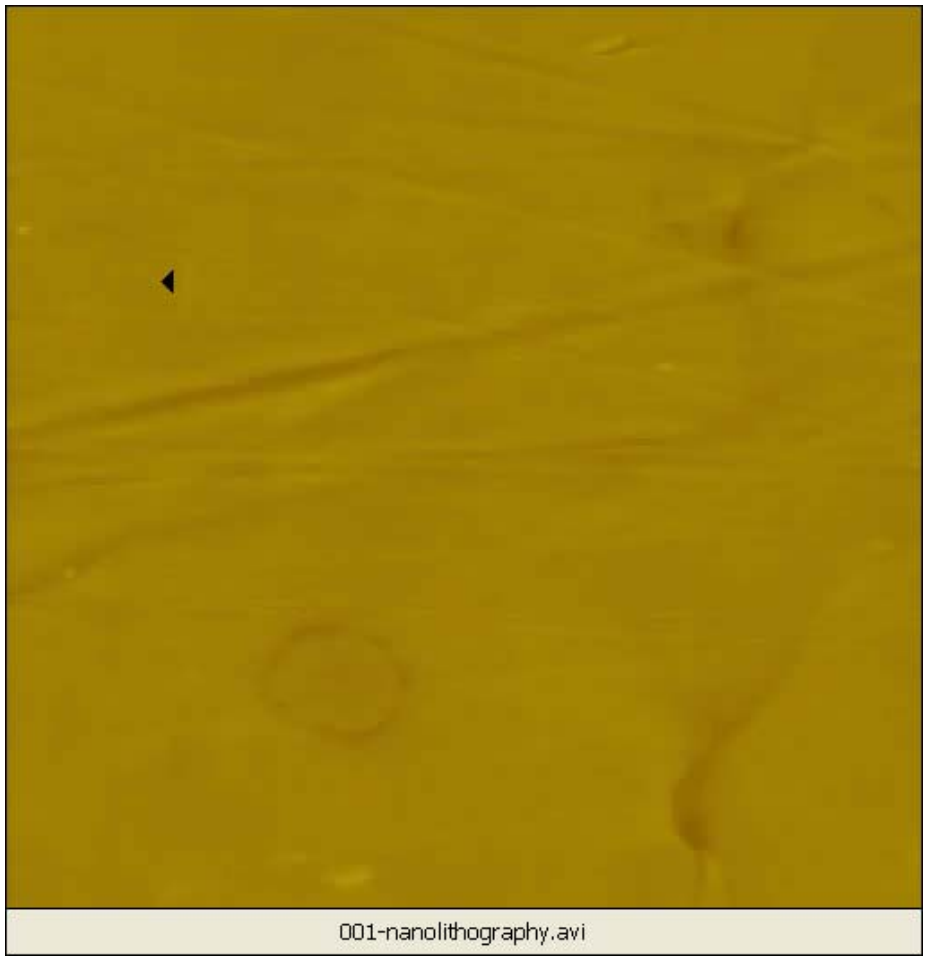
Classical Nanostructure 1/f noise vs. Quantum CNT Lorentz noise

- Wiener-Khtchine Theorem $FT\{psd(f)\}=<c(x_o+x)c(x_o)>$
- 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 $a=1.41A^o$



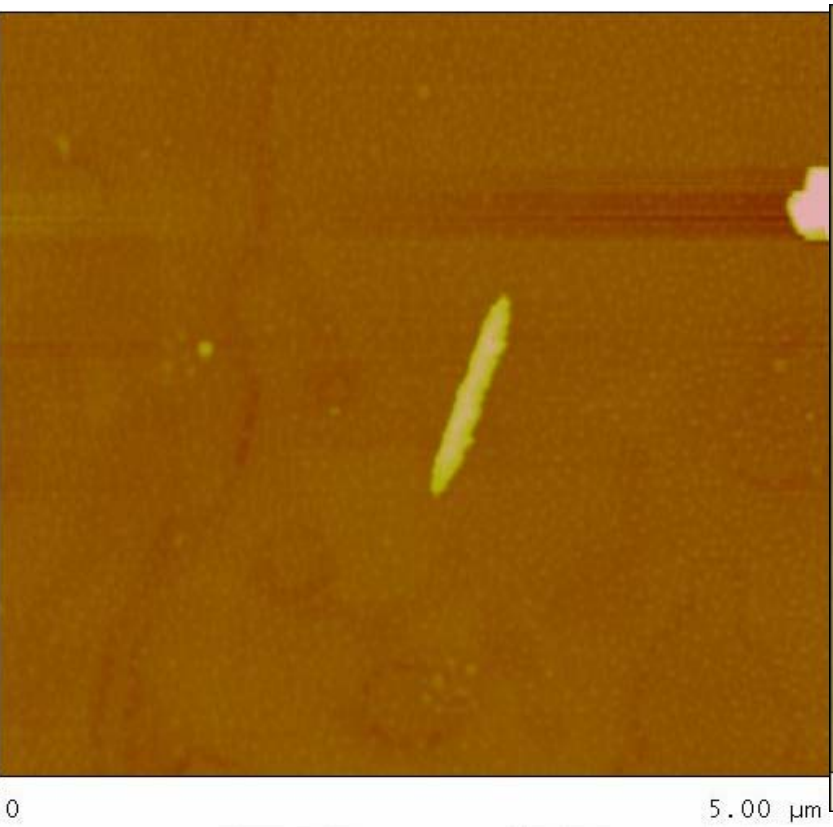
The picture shows a carbon nano tube (CNT) based IR detector array. Each pixel of the IR detector array consists of a multi-wall CNT with a proper tuned bandgap for detection of selected spectrum of the infra red.

Nanolithograph

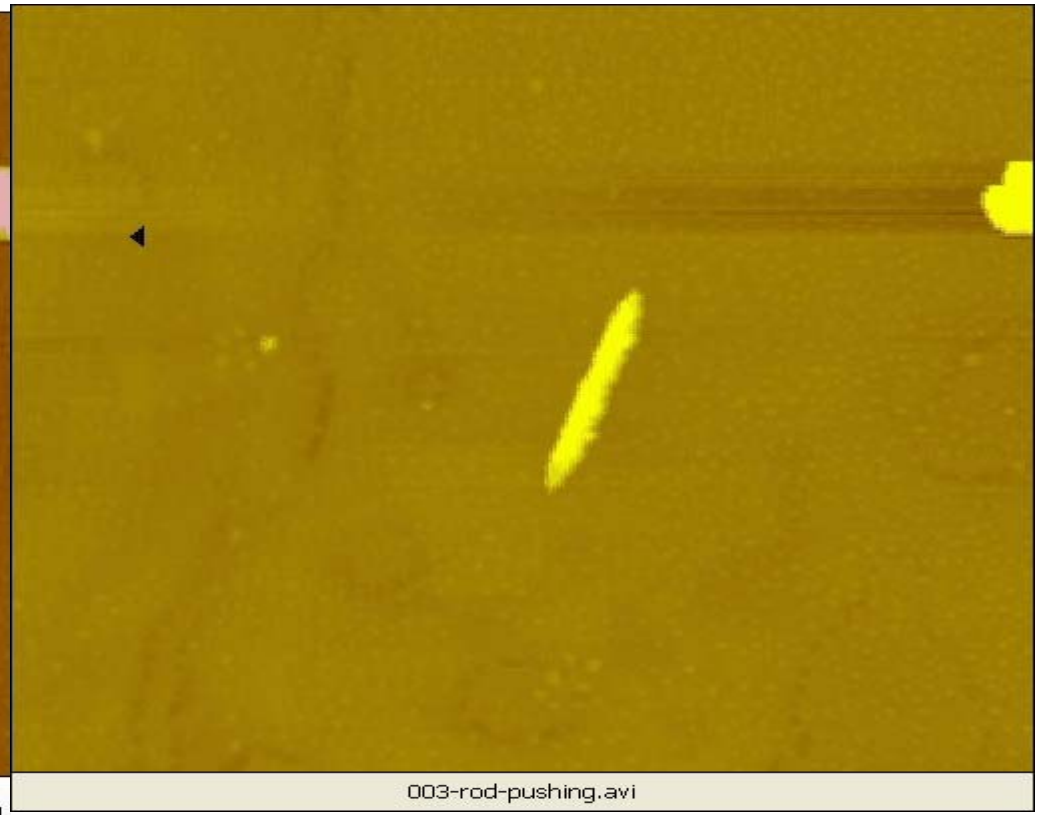


Nanoassembly Experiment

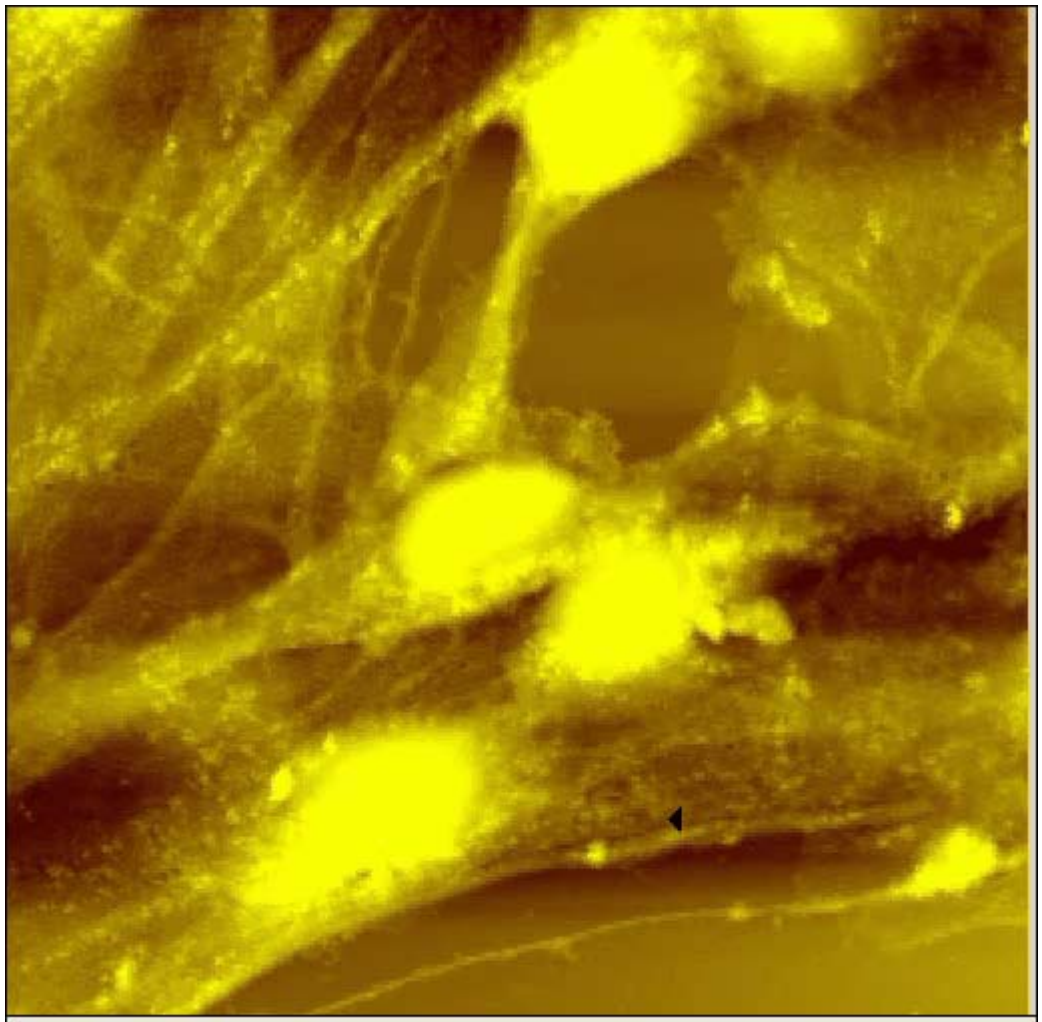
- Creating a fixture and then pushing a 100nm silver nanowire into the fixture (scanning size 5um)



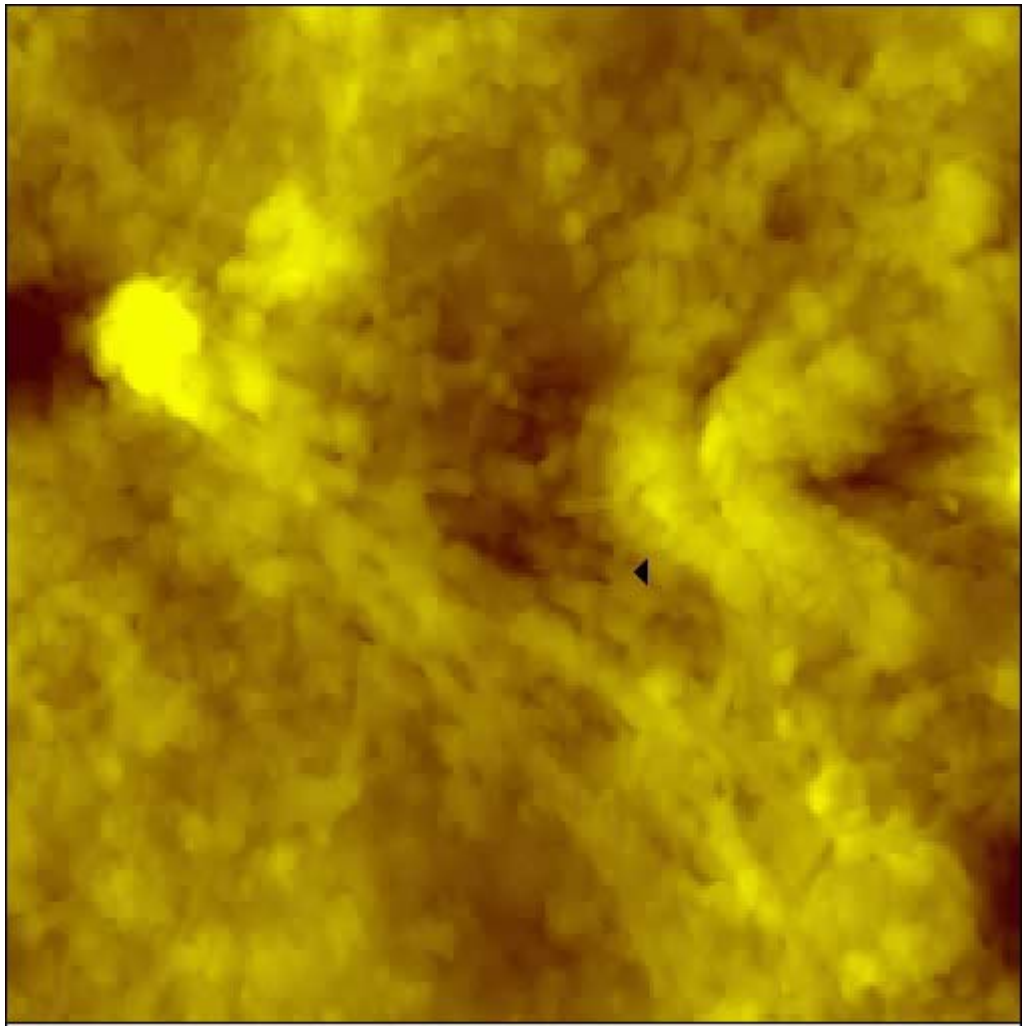
AFM image



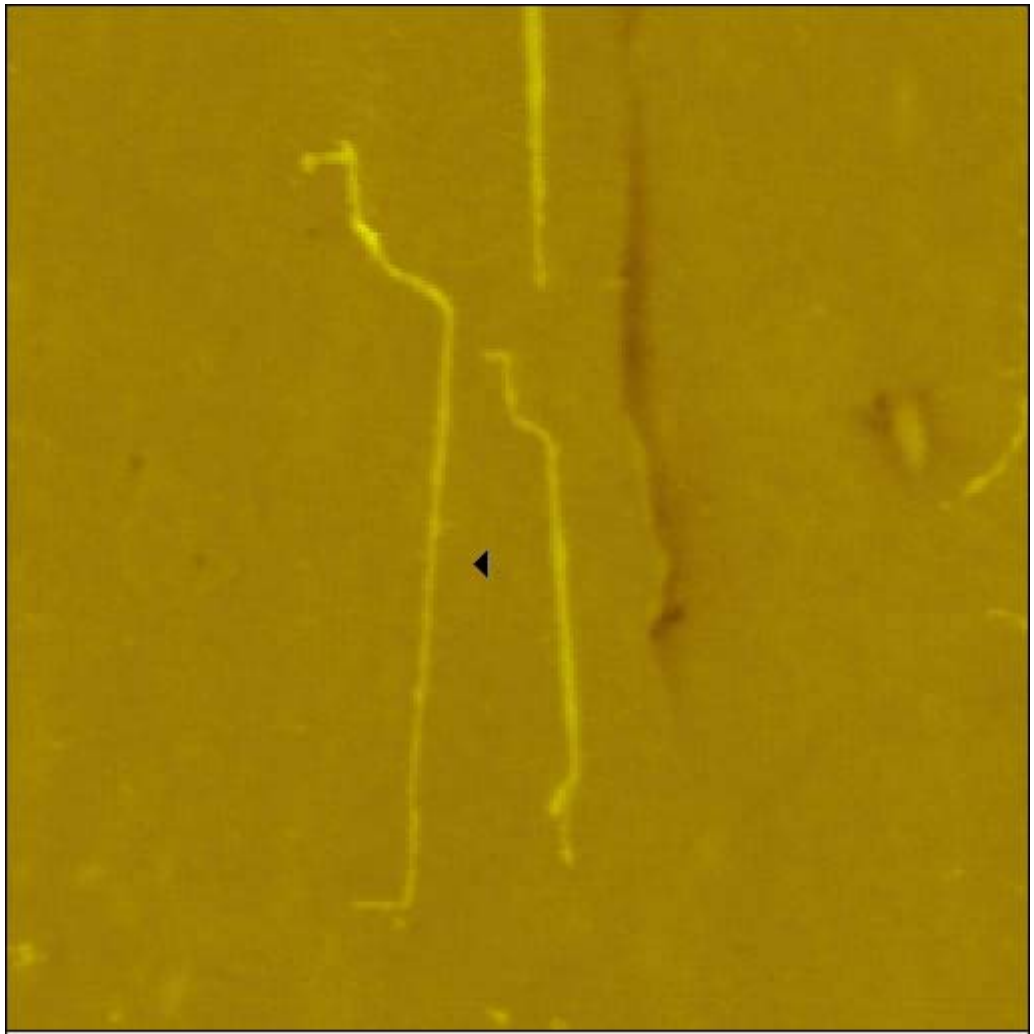
Real-time visual display



005-neuron-cutting.avi



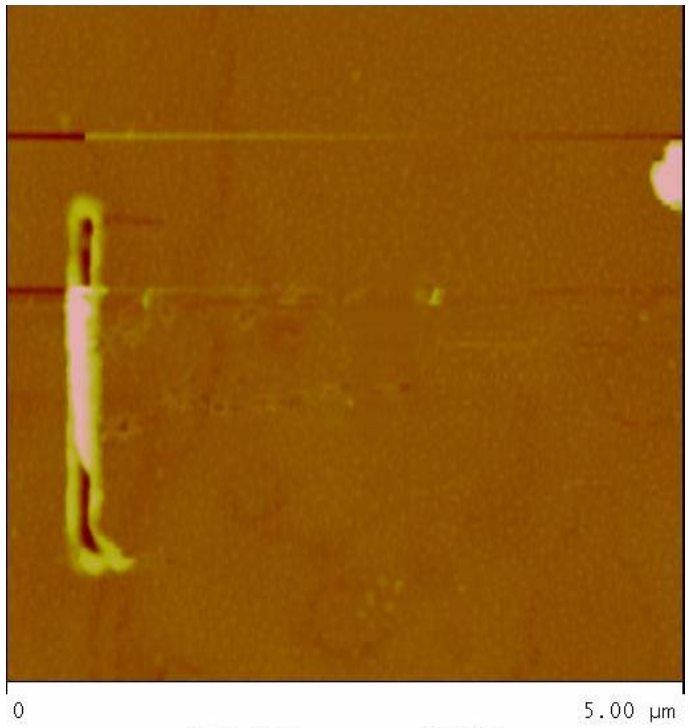
006-neuron-digging.avi



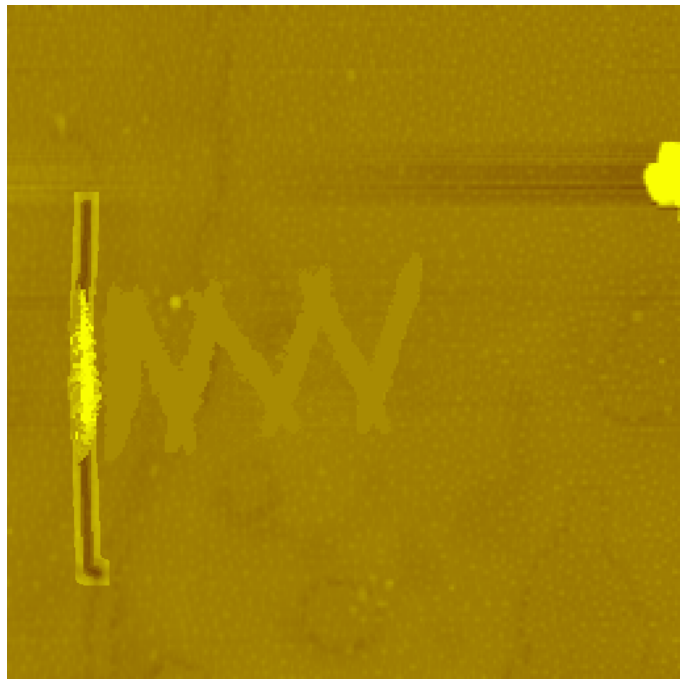
007-DNA-pushing.avi

Nanoassembly Experiment

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



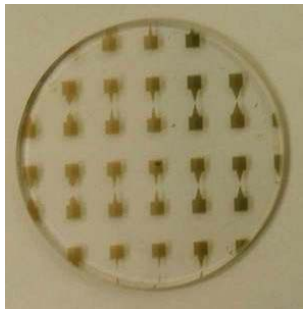
AFM image

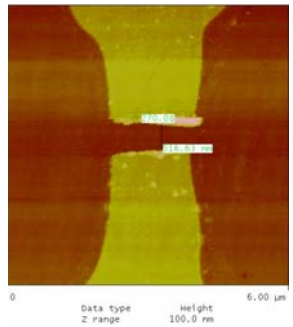


Real-time visual display

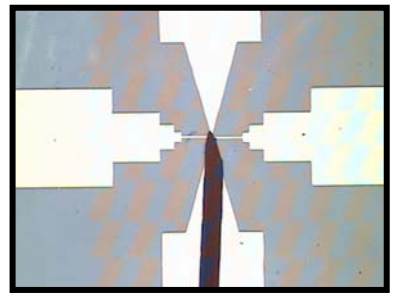
Fabrication Process

Substrate Fabrication

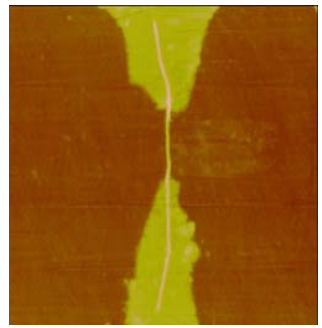




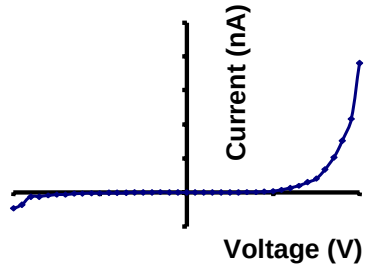
Nano lithography



CNT Deposition



CNT Assembly



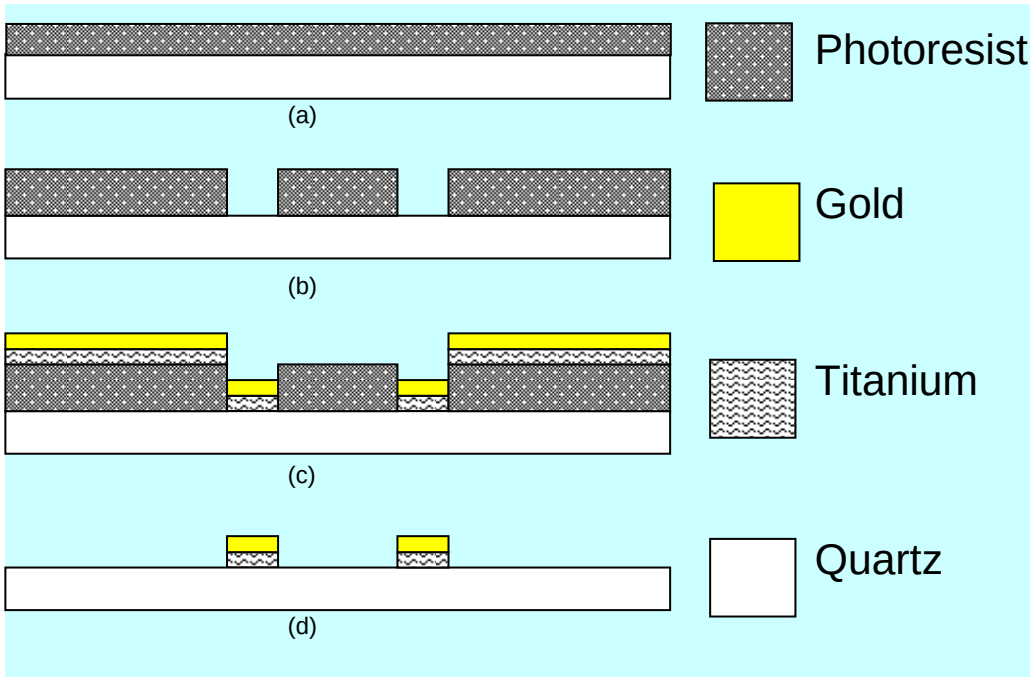
Band Gap Tuning

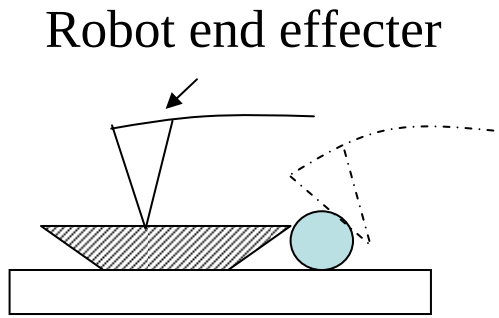
Chip Packaging

Final Testing

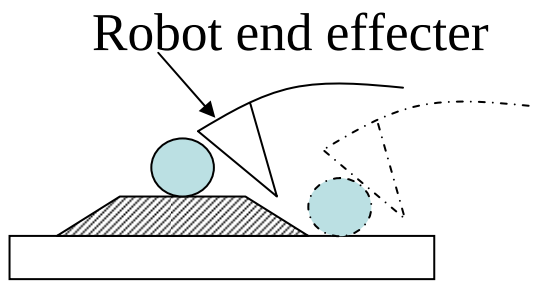
Substrate Fabrication

The electrode patterns are made from a lift-off process





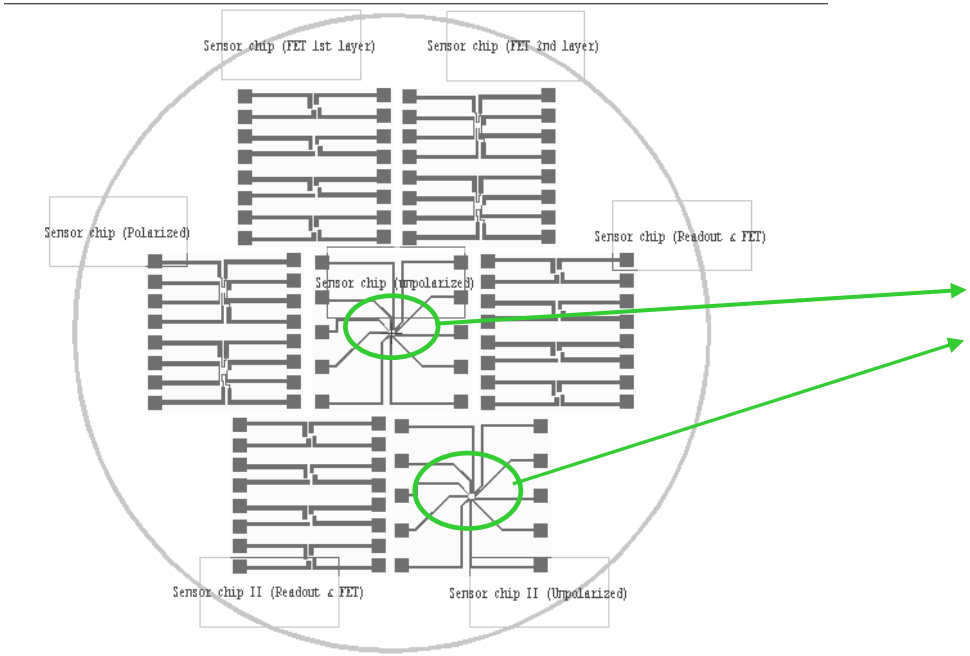
(a) etching process



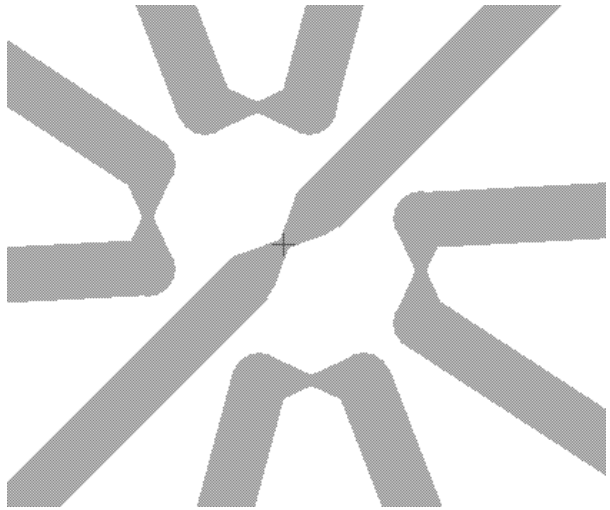
(b) lift-off

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.

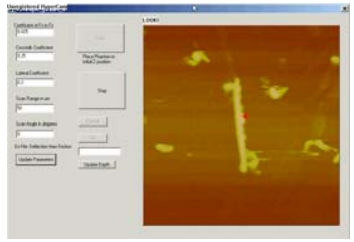


unpolarized single pixel



Fabrication and Assembly by Nano Robot

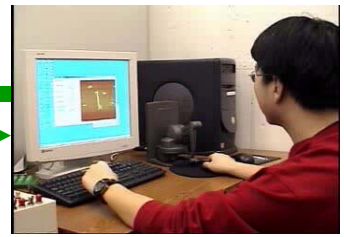
AFM Based Robotic System

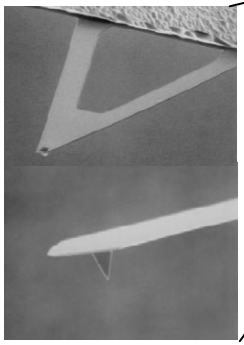


Real-time Videolized AFM Image Display

Control Command

Force and Image Info





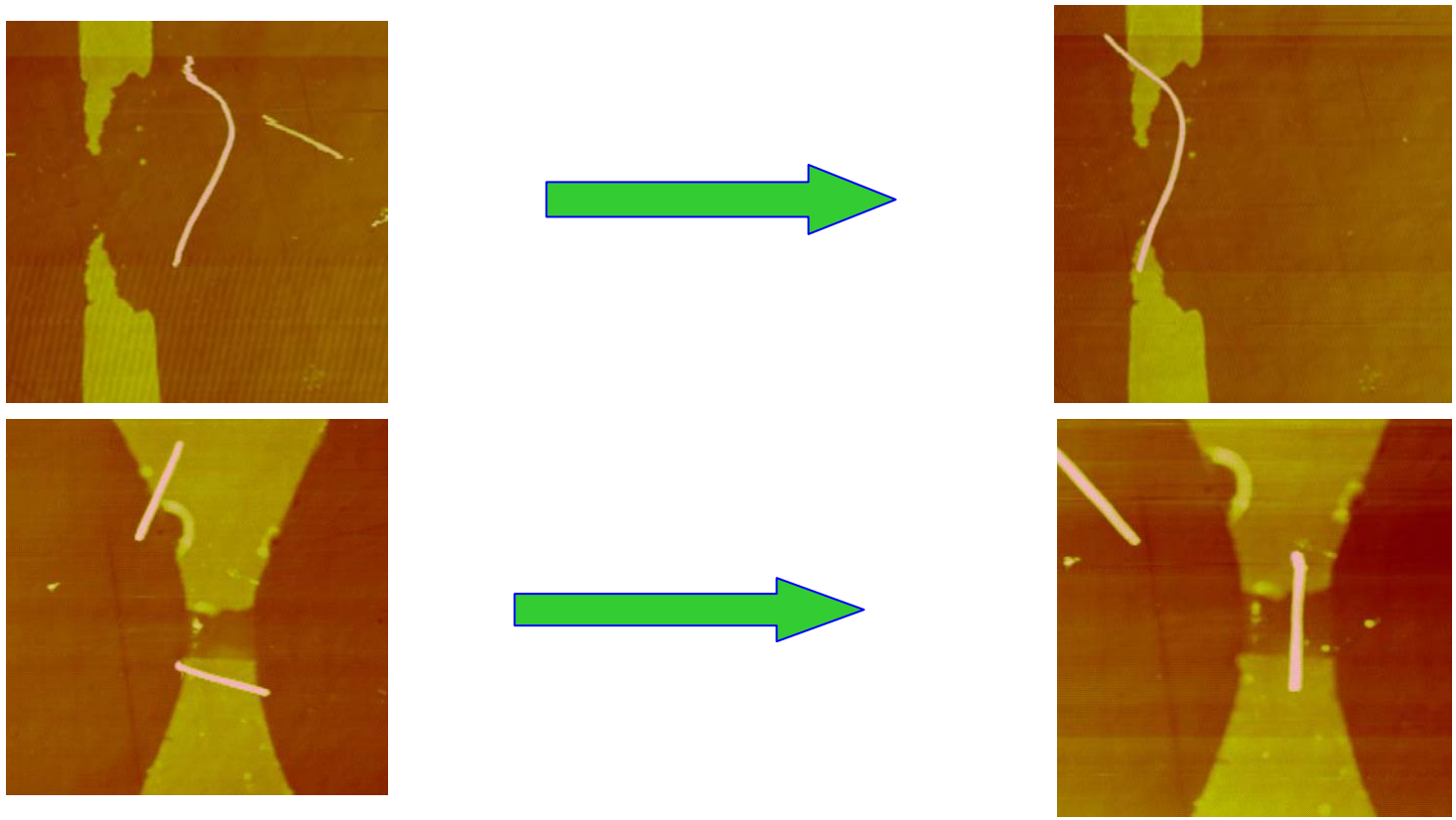
Robot End-Effector

Haptic Feedback

Command Generator

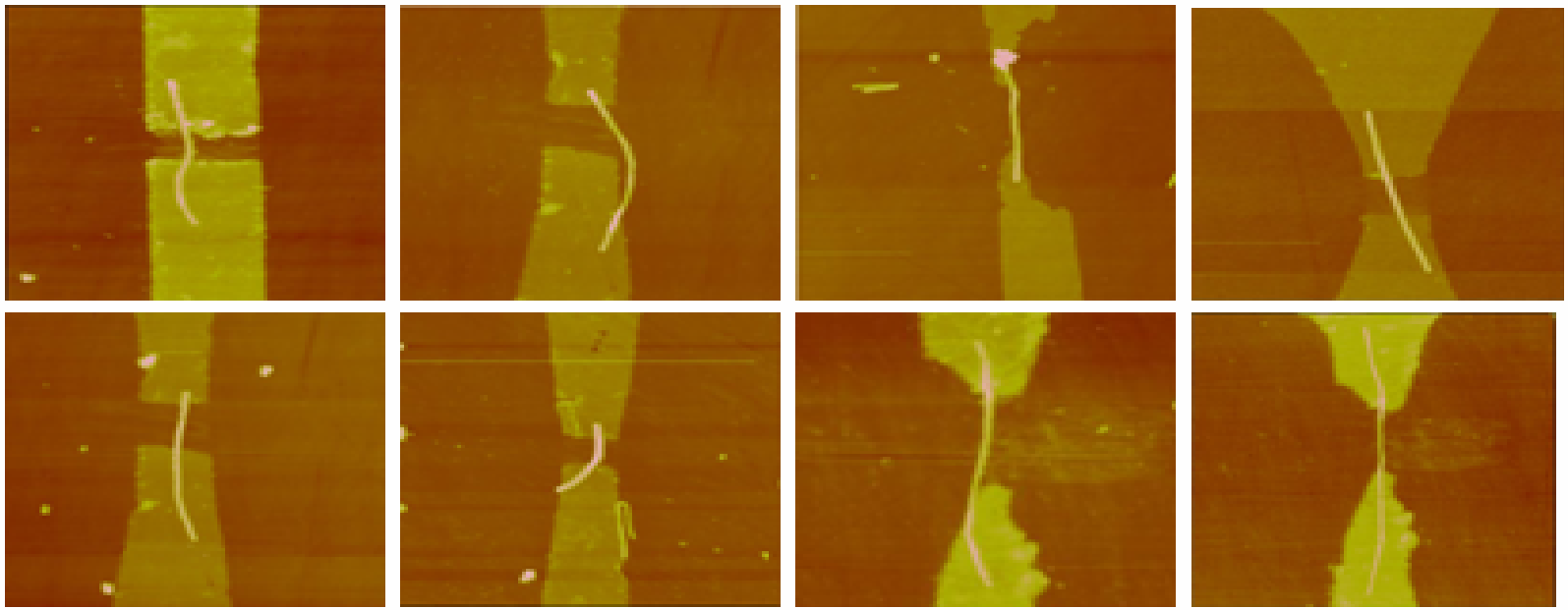
Placement of CNTs between Electrodes

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



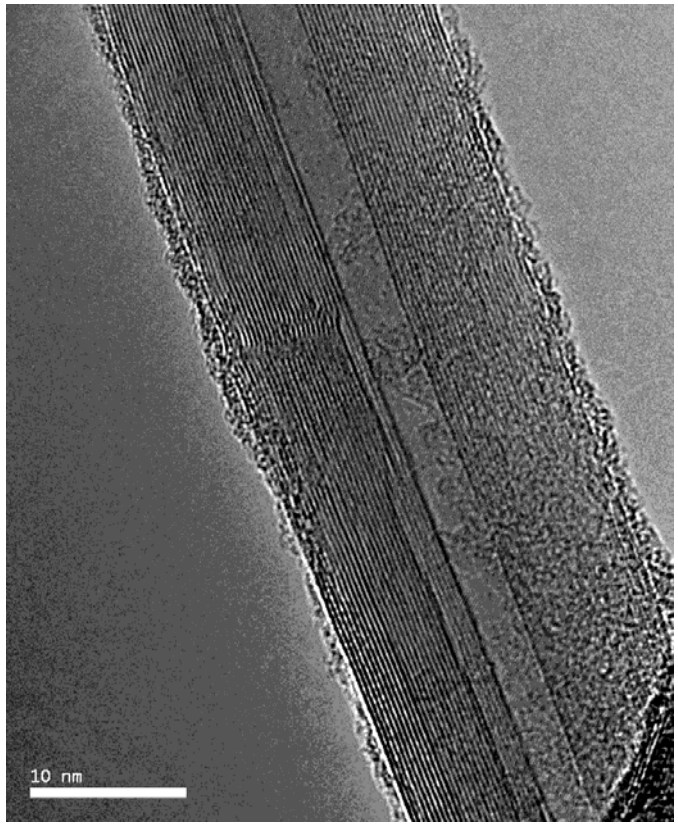
CNTs between Electrodes

- Assembled CNT based detectors

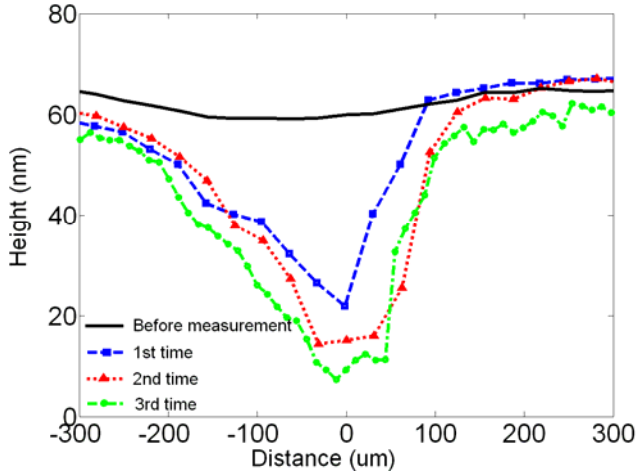


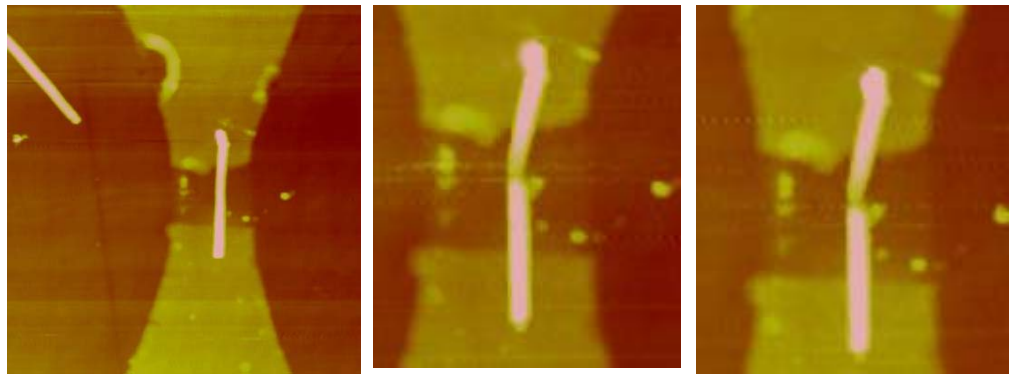
CNT Band Gap Tuning by Breakdown

TEM image of MWCNT

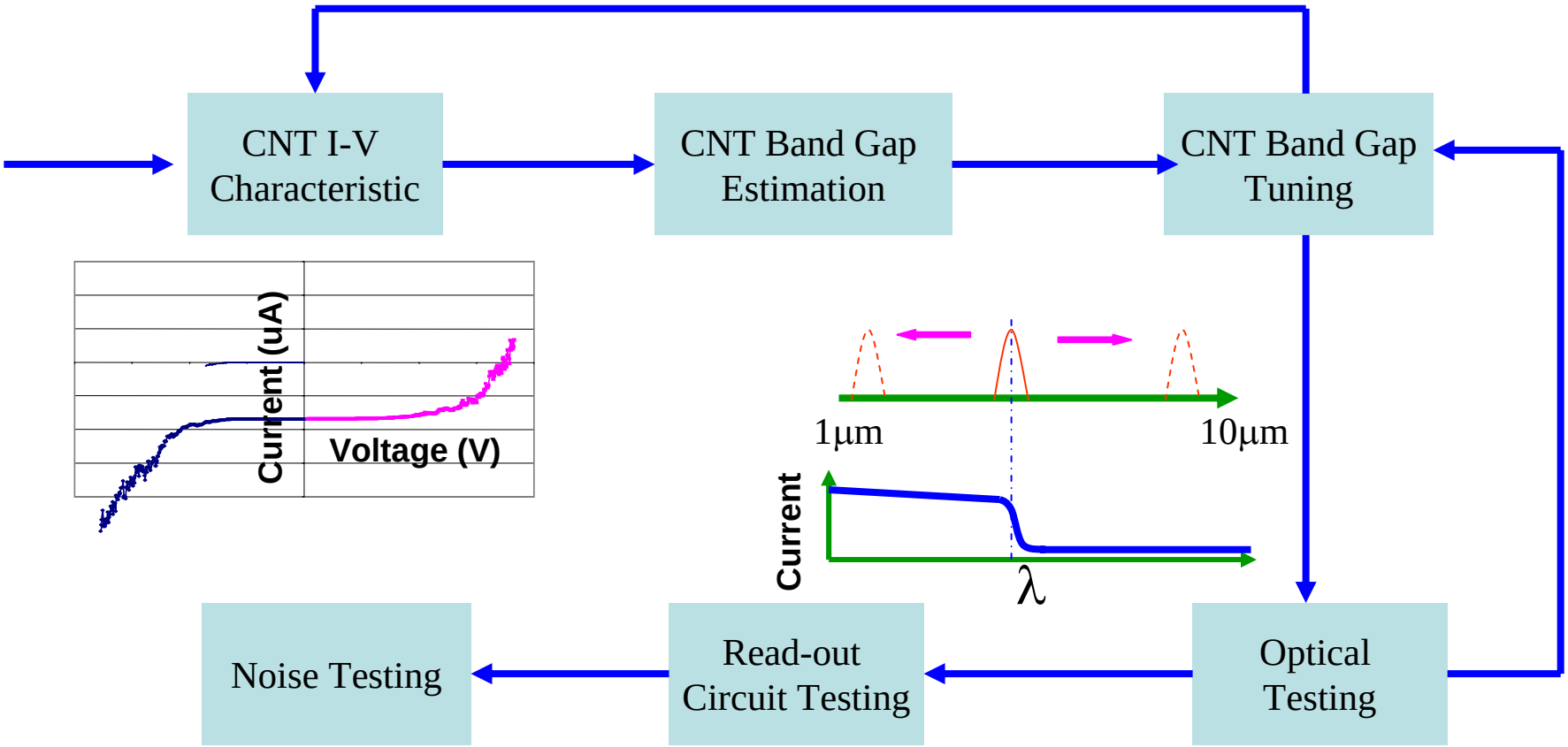


Topography of MWCNT



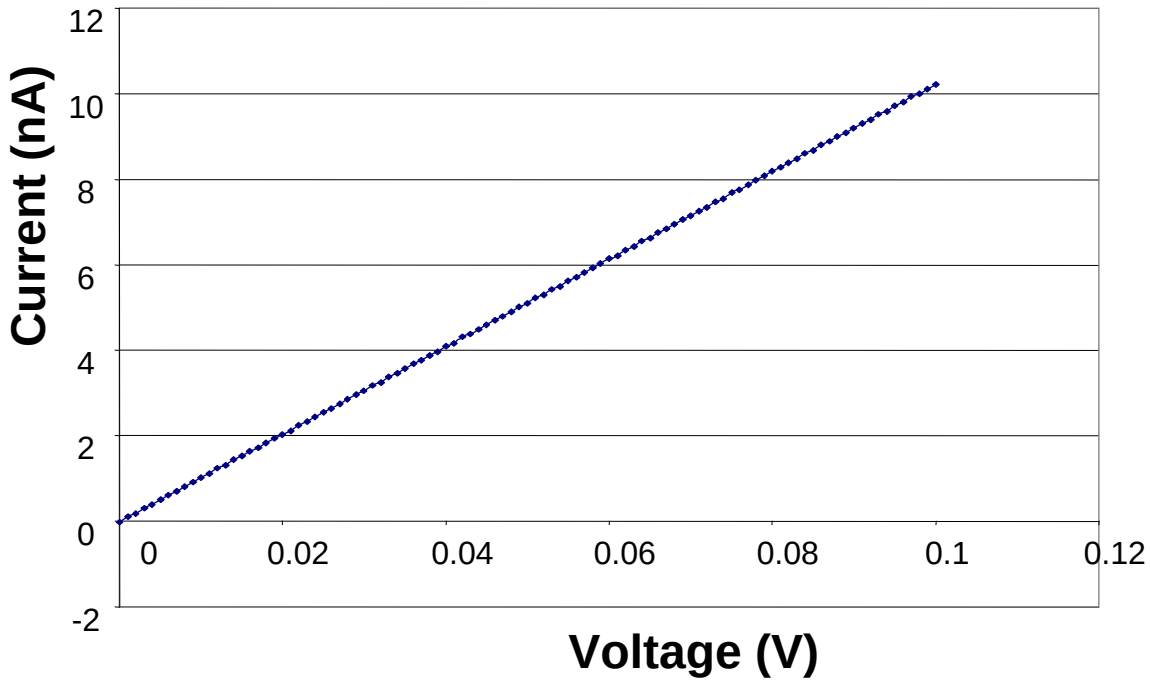


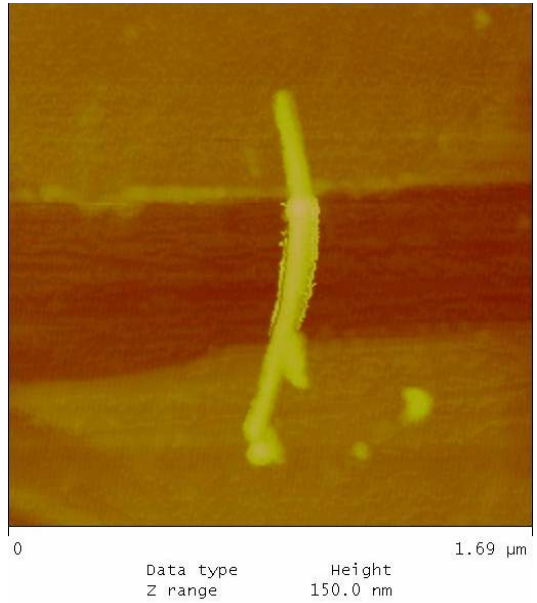
Testing and Results



I-V Characteristic of a CNT

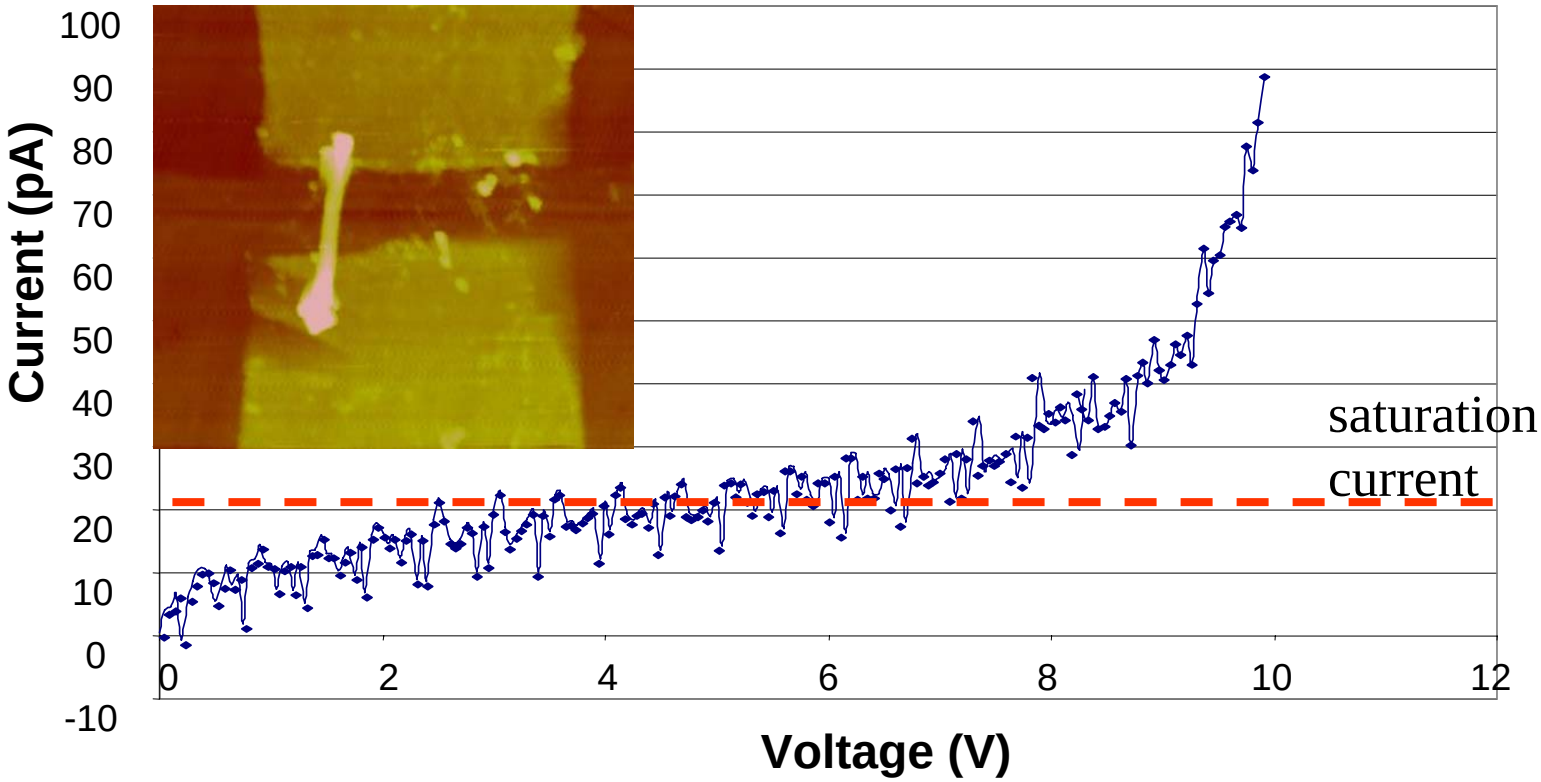
Metallic behavior of CNT, the resistance of CNT is very small. The figure shows the CNT in serial connection with 10M Ohm resistor





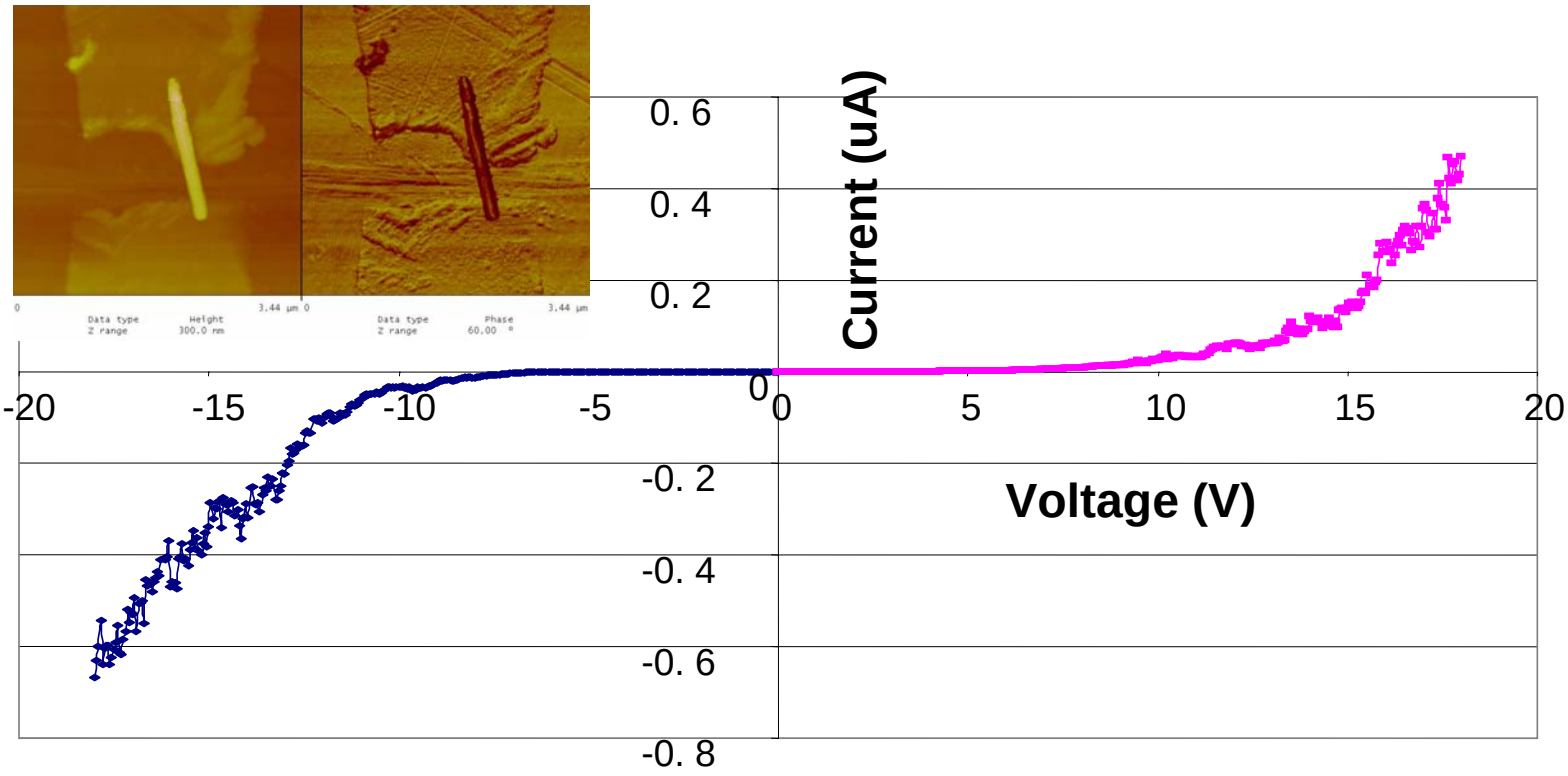
I-V Characteristic of a CNT

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)

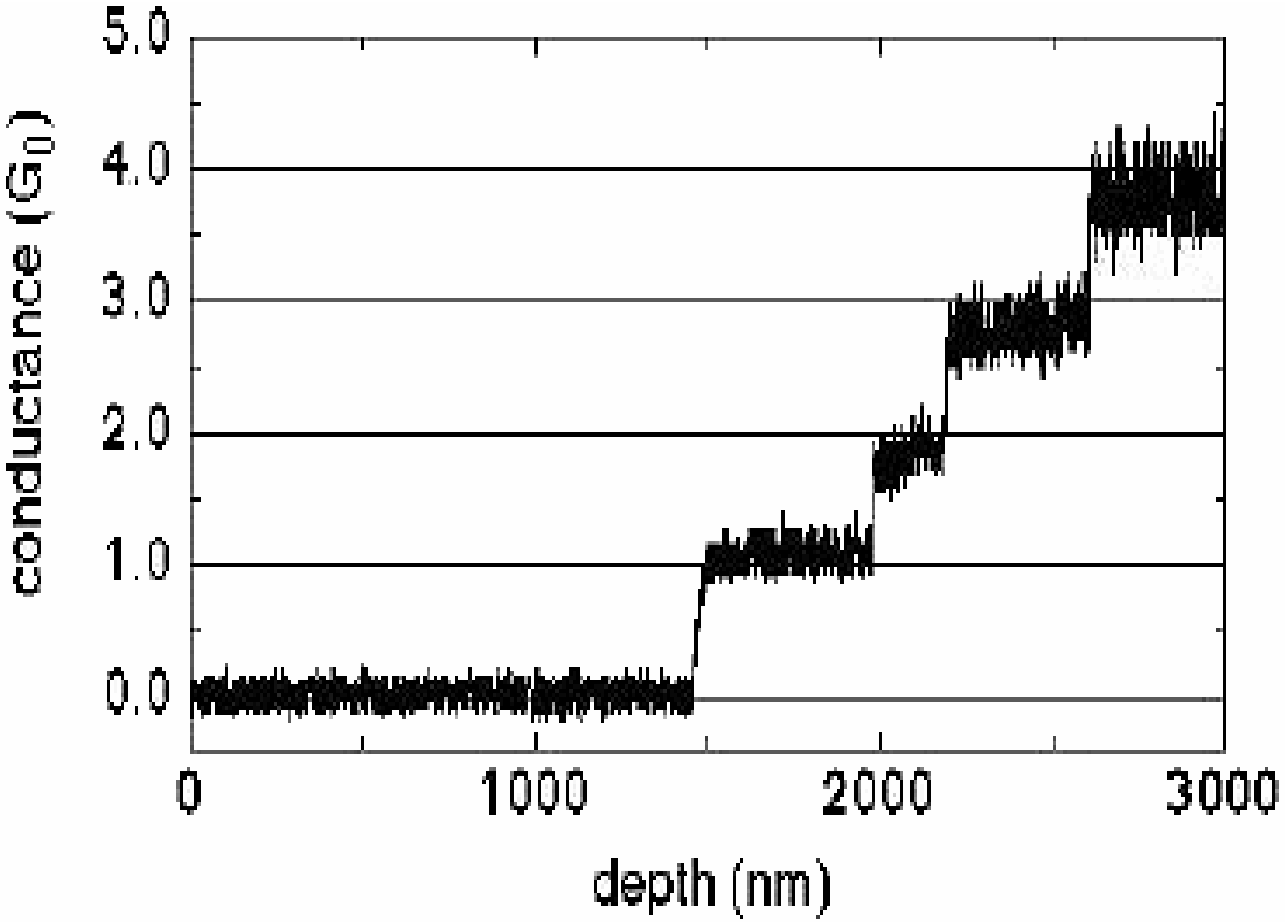


Smart Vision Sensors: Rods & Cons

- 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

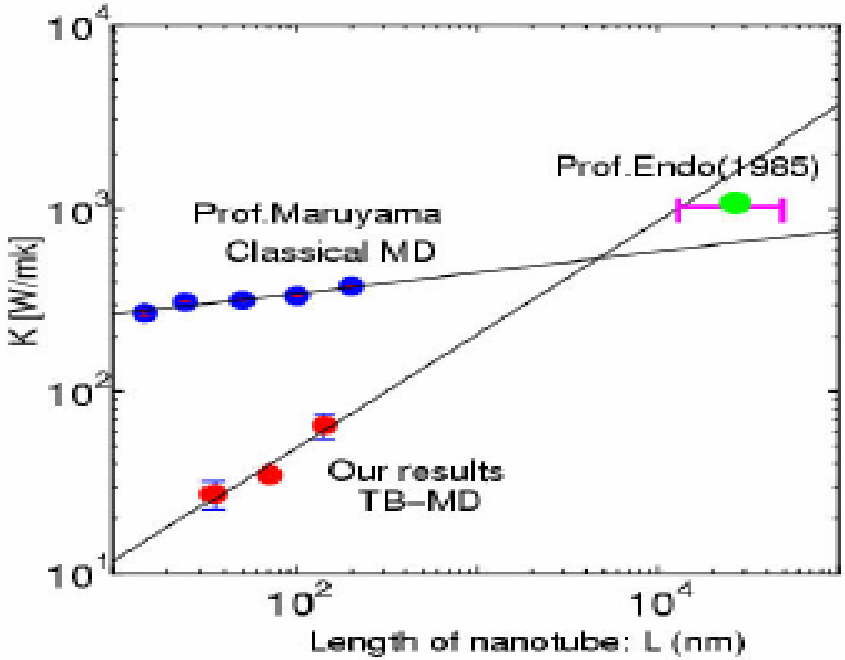


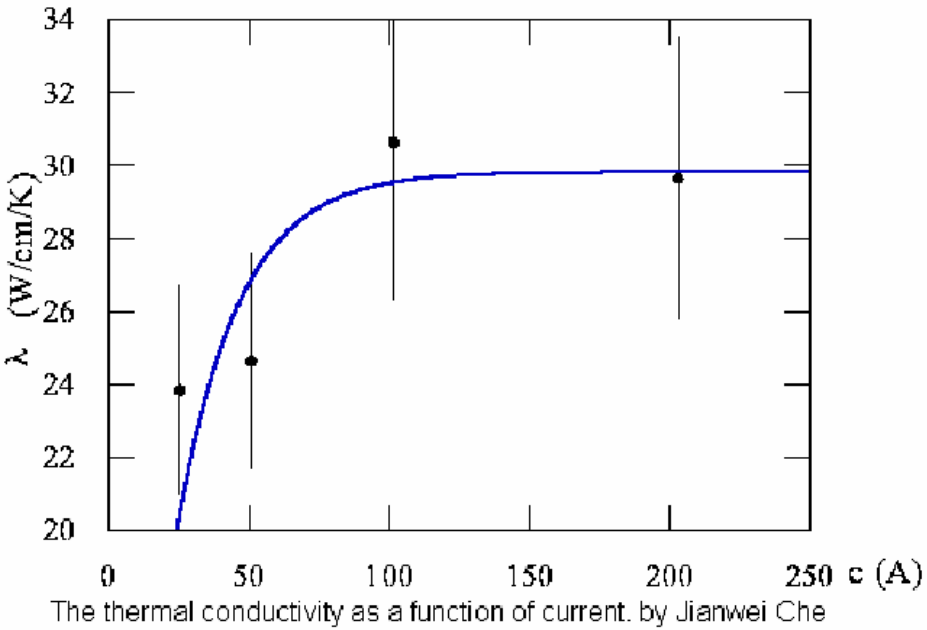
Above: A carbon nanotube is a quantum conductor. The conductance rises by 1 G_0 as the depth increases sufficently. G0= 2e2/h

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

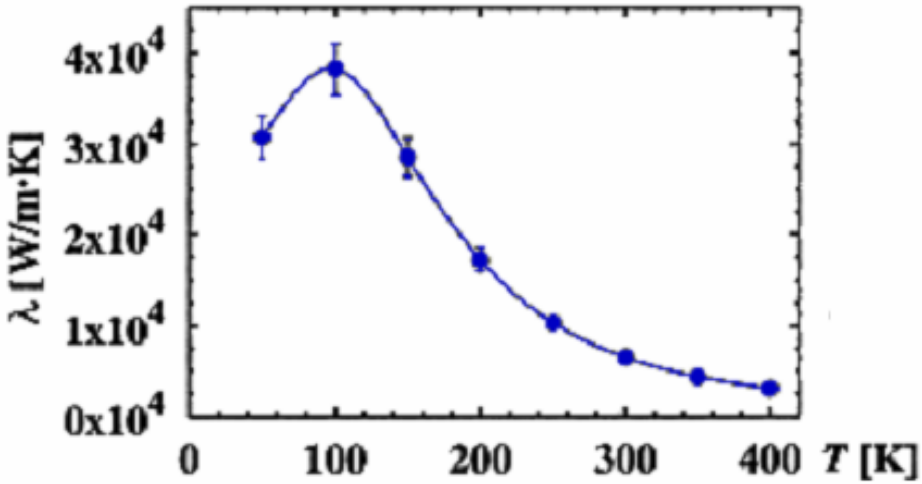
Thermal Transport in CNT

- 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))