Process steps for Field Emitter devices built on Silicon wafers
And 3D Photovoltaics on Silicon wafers

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Field Emitters

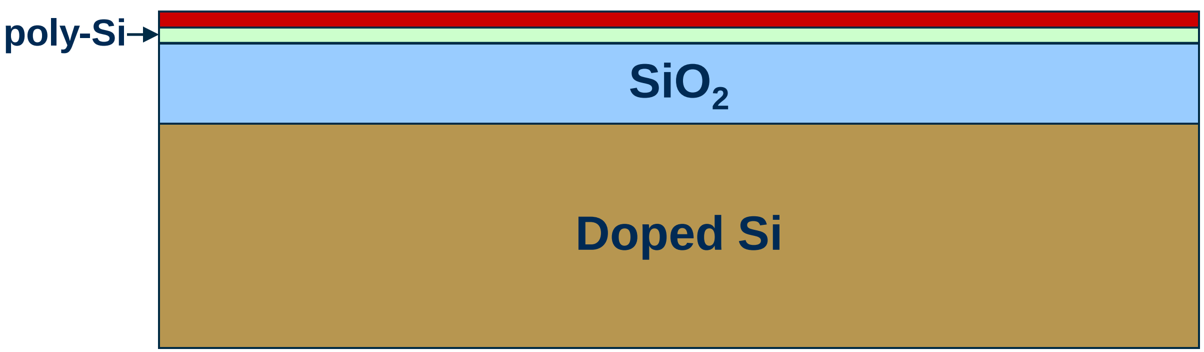
Doped Si

- Deposit SiO2 (~10μm)
- Variable for Height

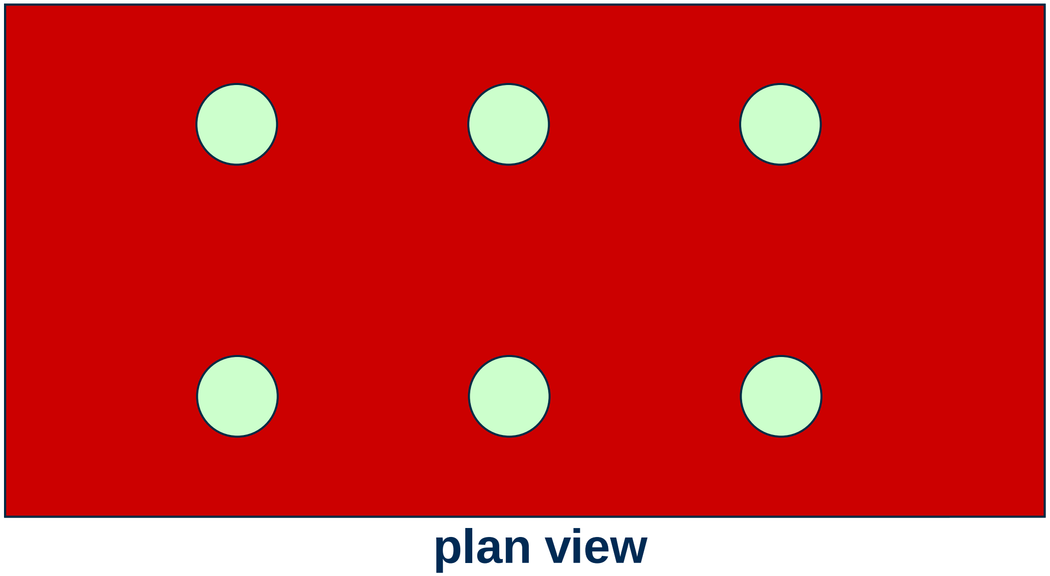
- Deposit gate
- (poly Si or Cr, ~200nm)

Spincoat Photoresist

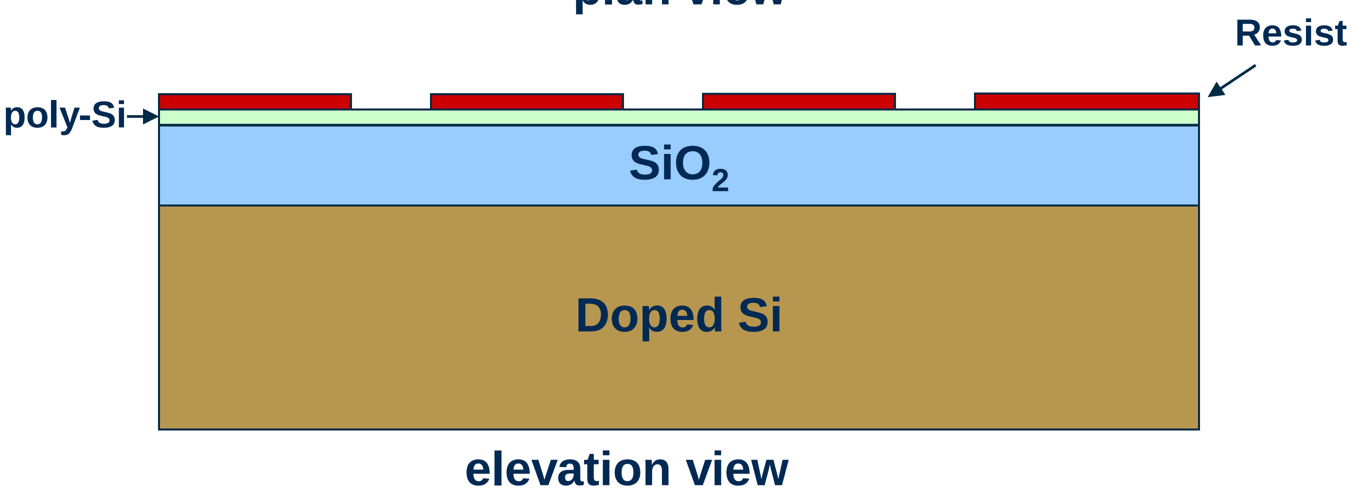
plan view

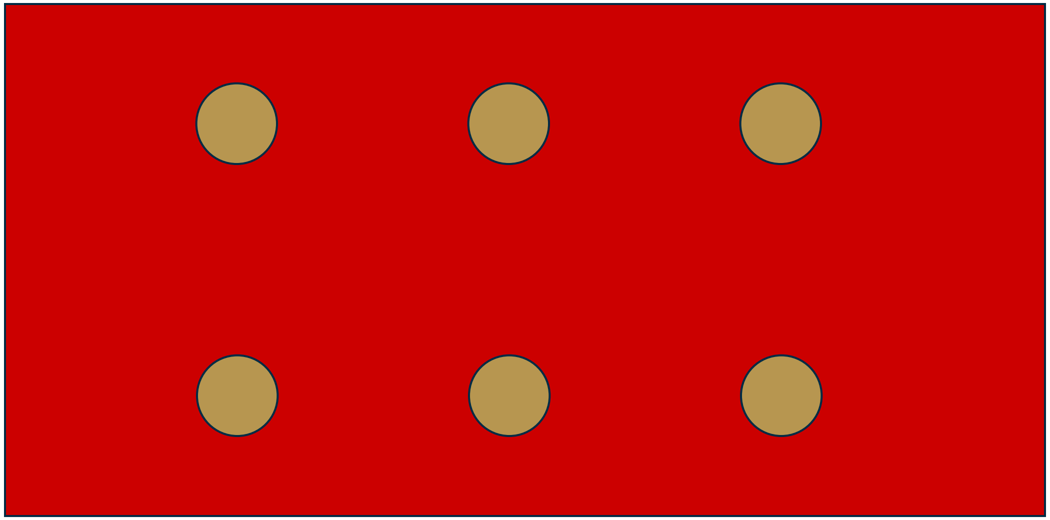


elevation view



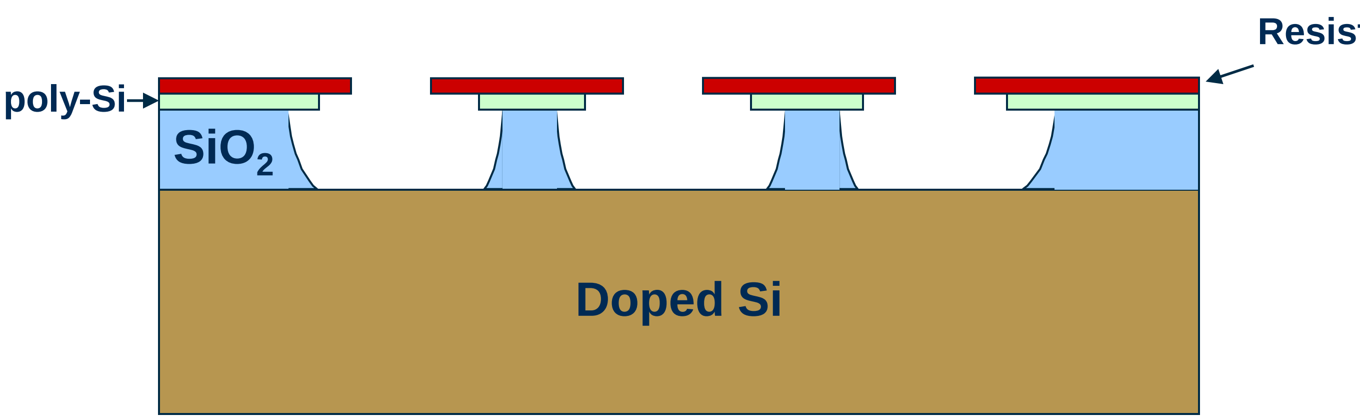
- Pattern
- Develop





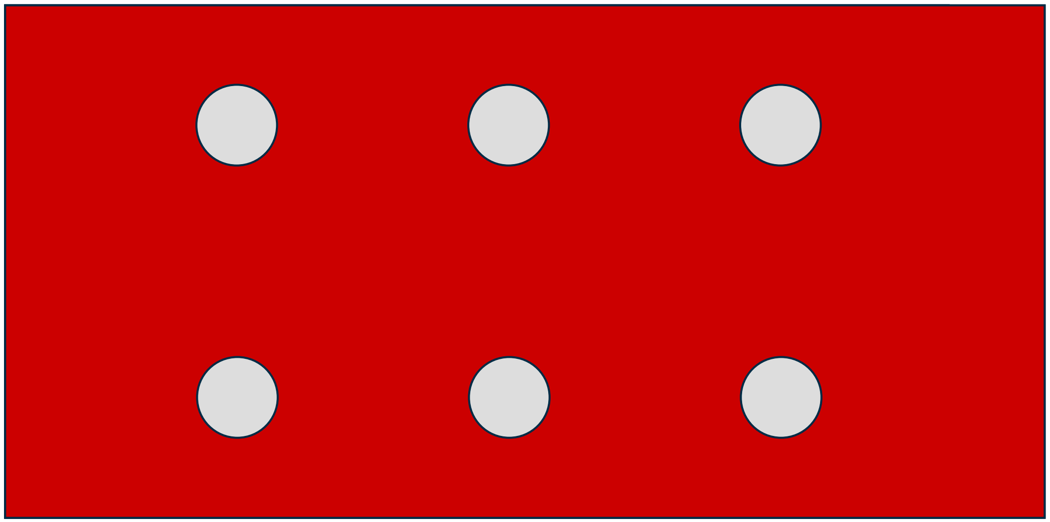
plan view

- Etch gate and insulator isotropically

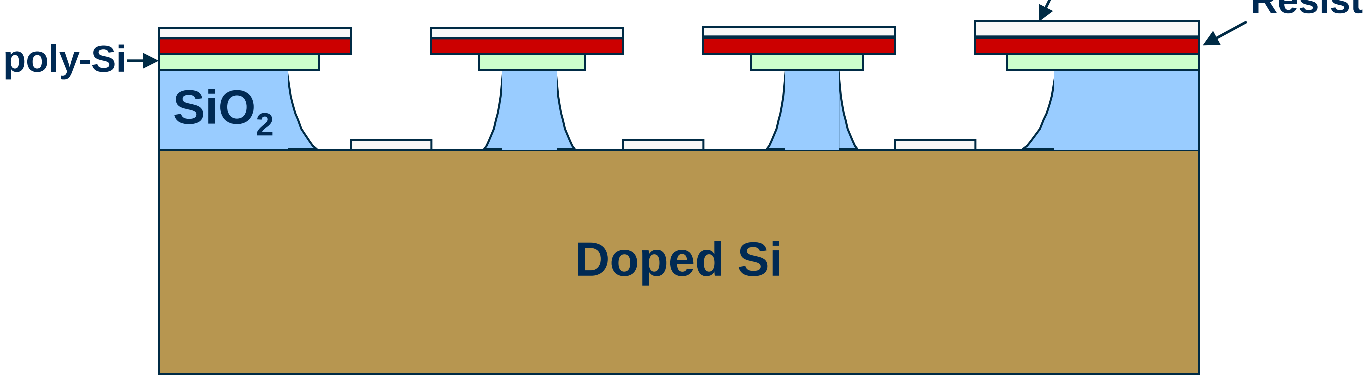


elevation view

- Deposit catalyst metal
- Fe shown
- Ni possible with barrier layers

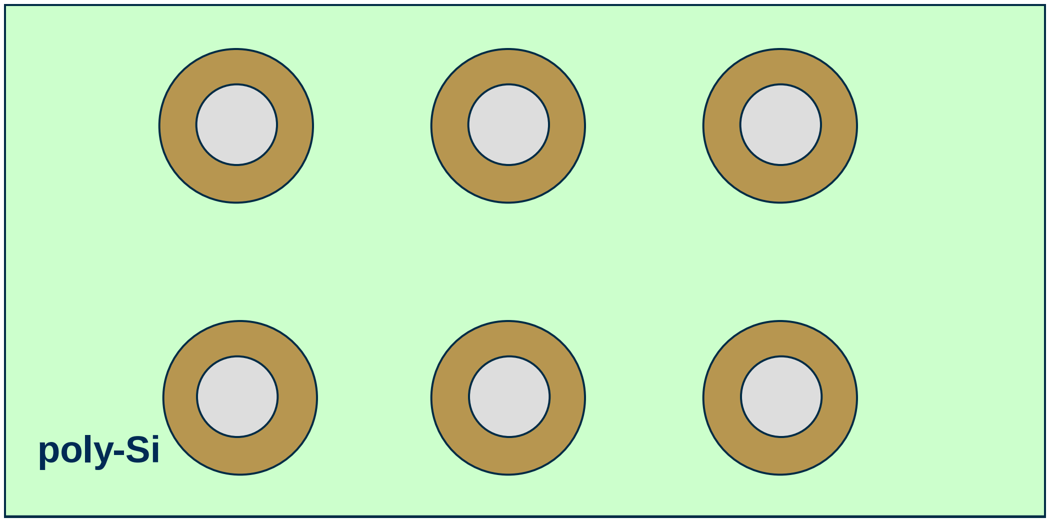


plan view

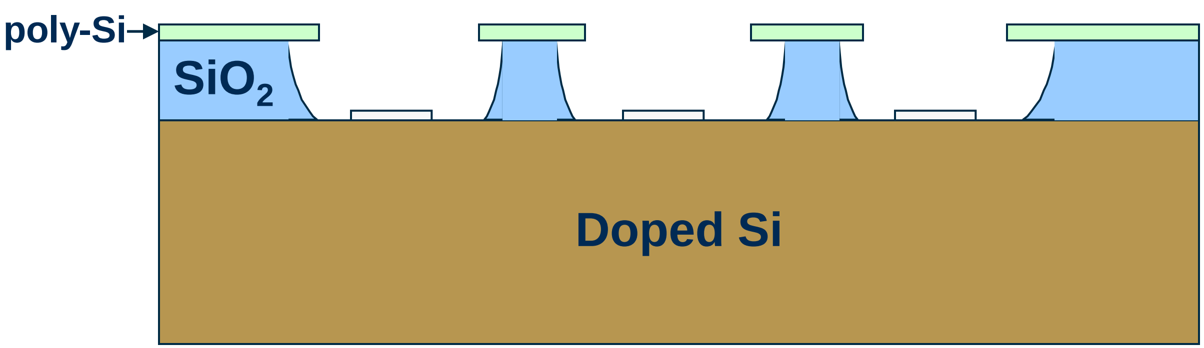


elevation view

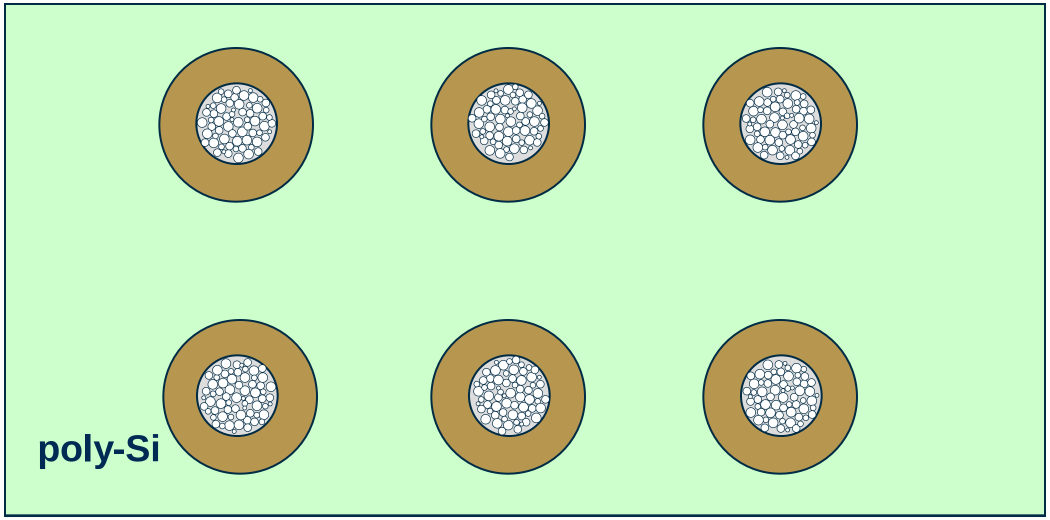
Lift off & Dice



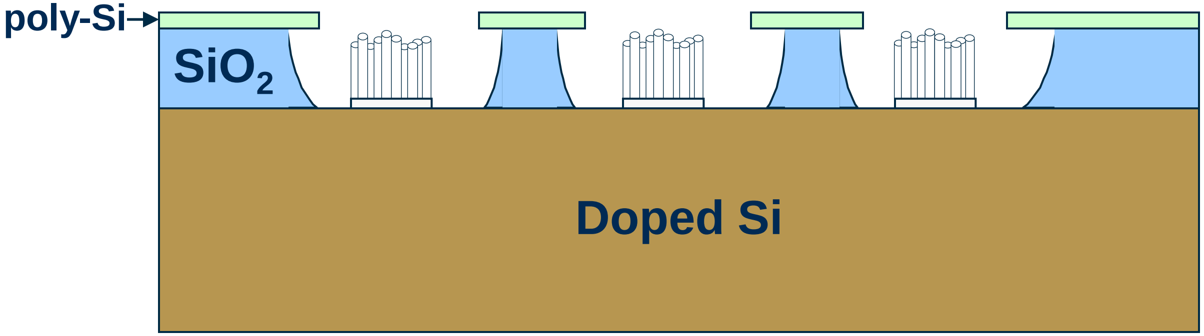
plan view



elevation view

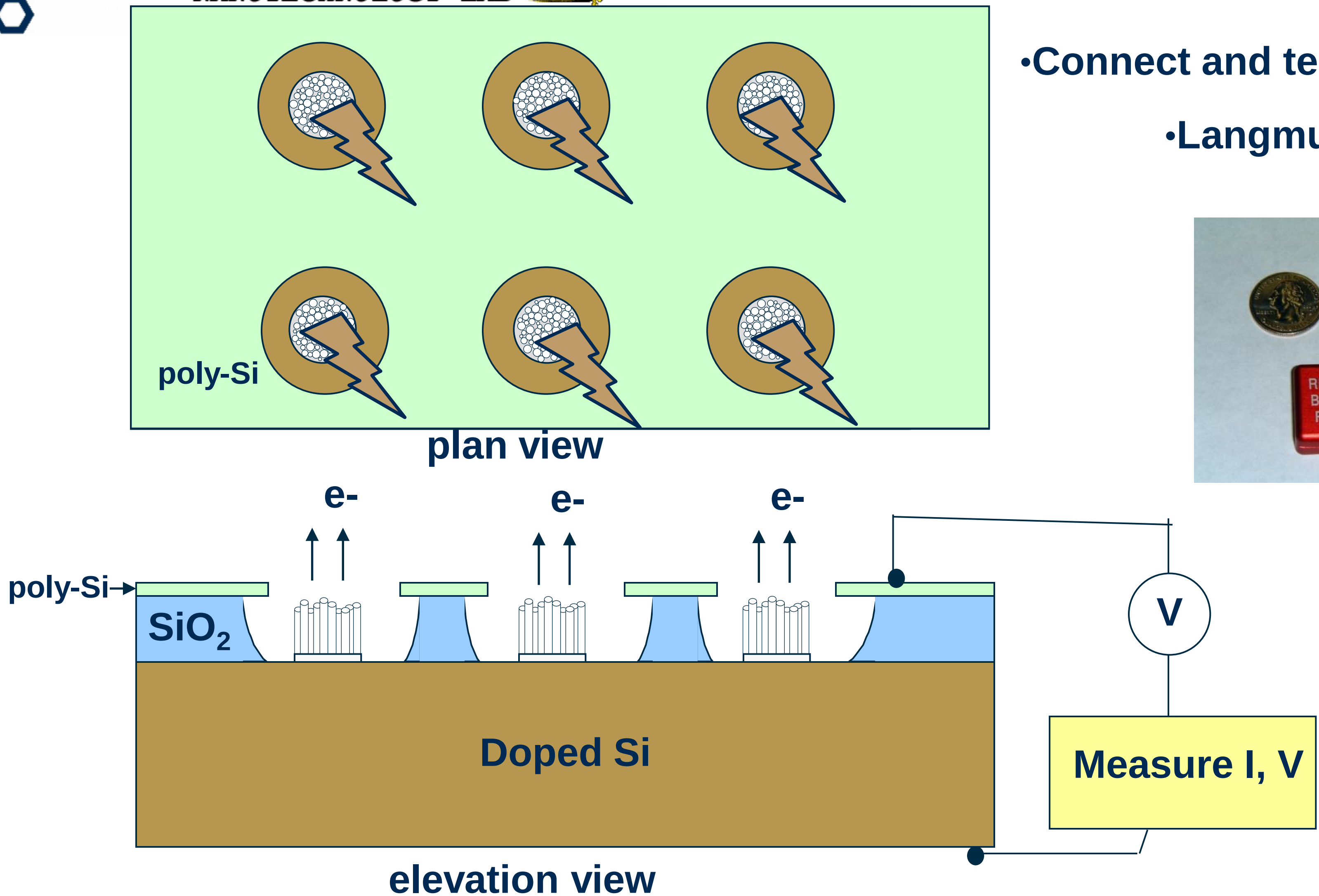


plan view



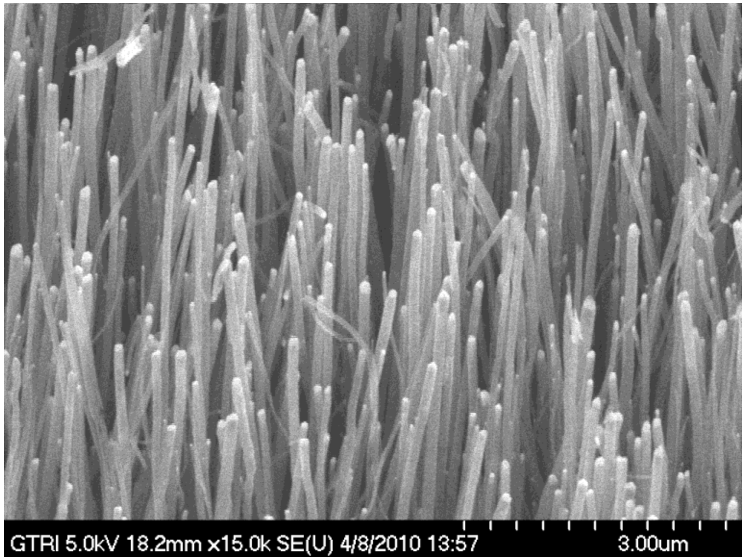
elevation view

- Grow CNTs



•Connect and test @ HPEPL

•Langmuir Probe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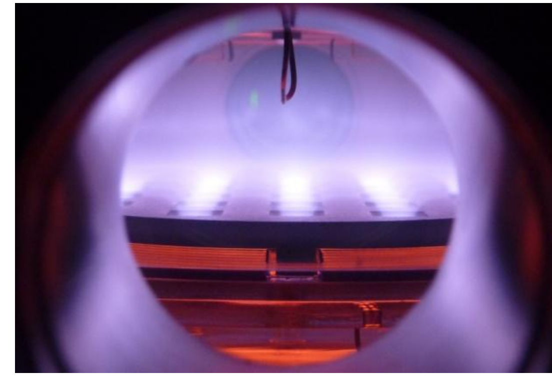
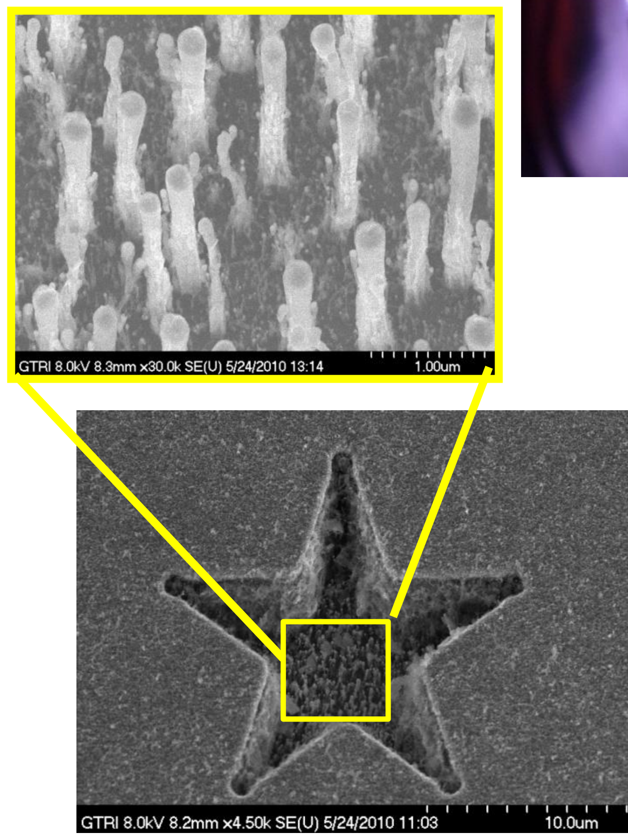
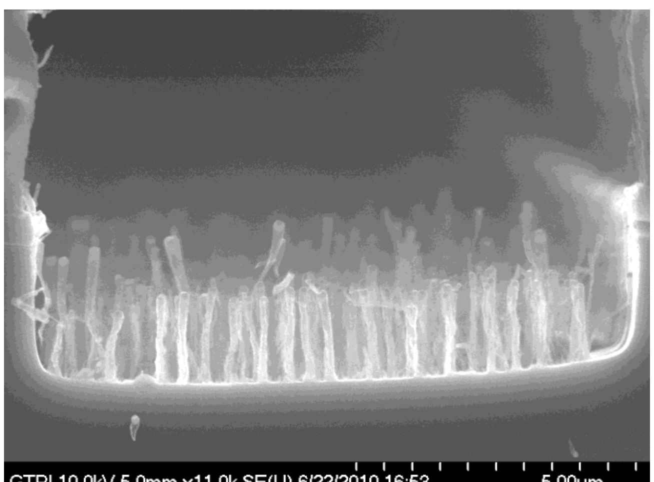
3.00um




GTRI 8.0kV 8.3mm x30.0k SE(U) 5/24/2010 13:14
1.00um
GTRI 8.0kV 8.2mm x4.50k SE(U) 5/24/2010 11:03
10.0um


GTRI 10.0kV 5.0mm x11.0k SE(U) 6/22/2010 16:53
5.00um

CNT growth parameter for CNTs ≤ 2µm

CVD growth:

•N_2 and NH_3 flowed at 100sccm and 160scmm

•Temperature ramp of 300°C/min until 650°C (top and bottom heat)

•Annealed at 650°C for 2min

•Plasma Ignited: 80W, 15kHz, 800V

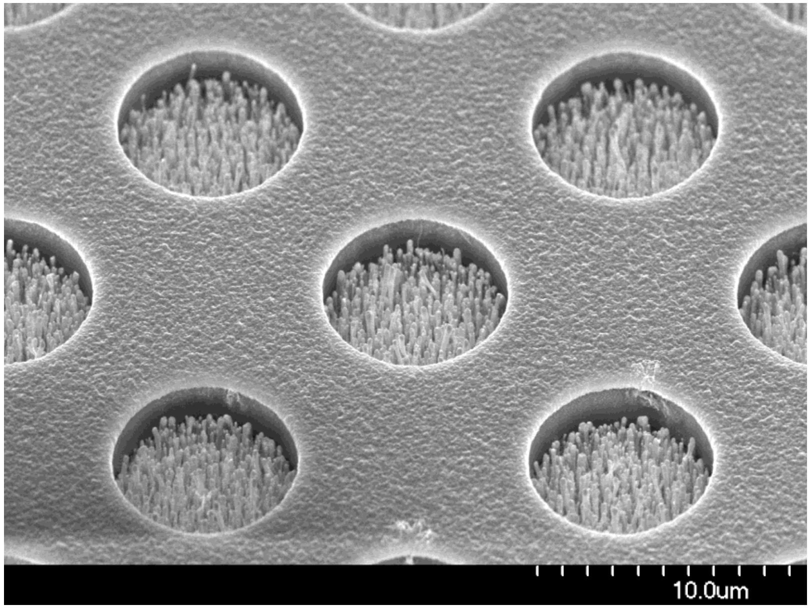
•Pressure controller activated: $P_{chamber}$ = 6mbar

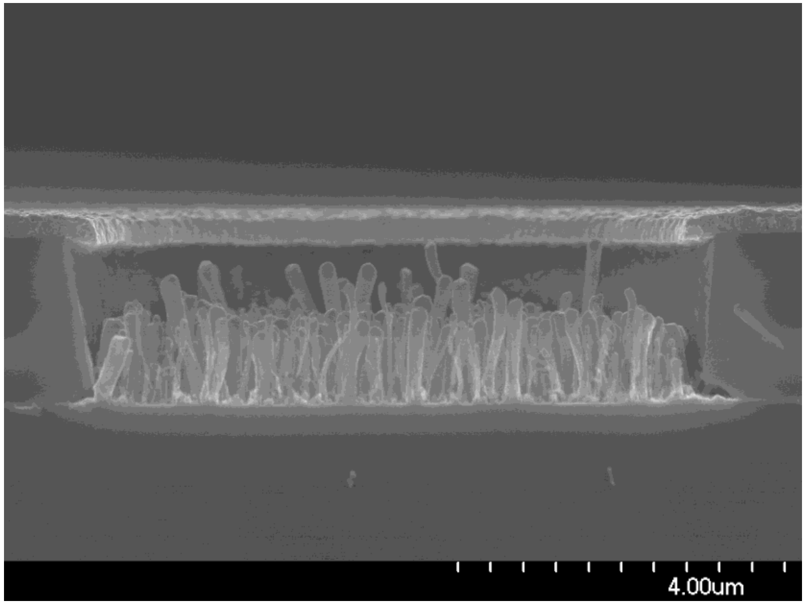
•Annealed under NH_3 plasma for 3 min while T raised to 750°C at rate of 200°C/min

•C2H2 (40sccm) introduced at end of plasma anneal

•Growth time = 6min

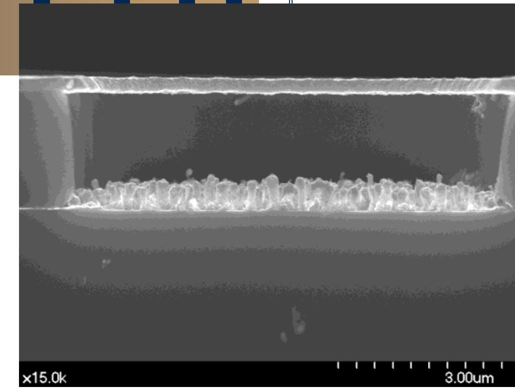
•Plasma extinguished, cooled under N_2 flow until T <400°C. Opened to atmosphere



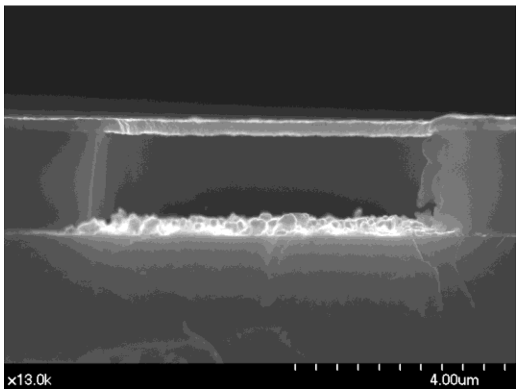


Influence of Temperature on CNT growth

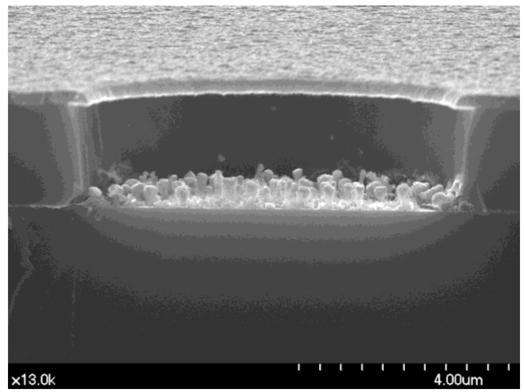
- Below 725 C – Catalyst does not sufficiently create 'synthesis islands'. Short, fat Carbon Fiber like 'CNTs' result
- Around 725 C – islands initiate growth, but rate of growth is limited
- 750 C - growth rate of ~0.3μm/min
- 775 C – some smaller islands, higher growth rate of smaller diameter CNTs
- 800 C – increased Ni diffusion into Si, few catalyst island remain on surface, sparse CNT growth, much lower diameter. Rate is similar to 750-775 range with larger variance



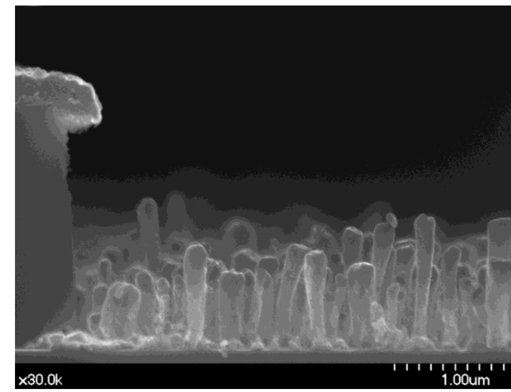
650 C



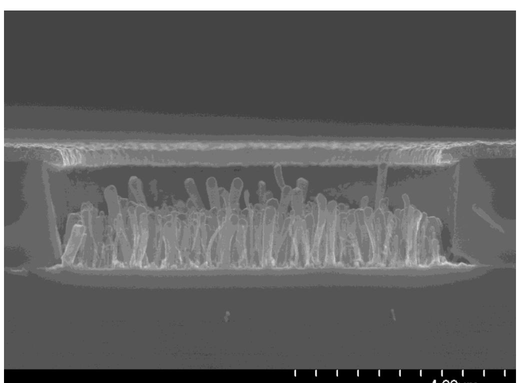
675 C



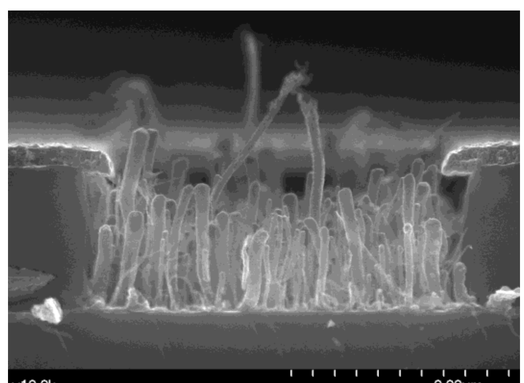
700 C



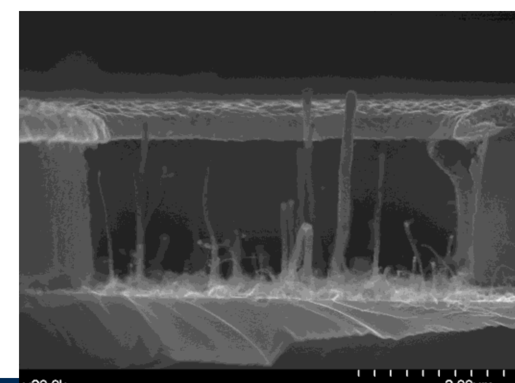
725 C



750 C

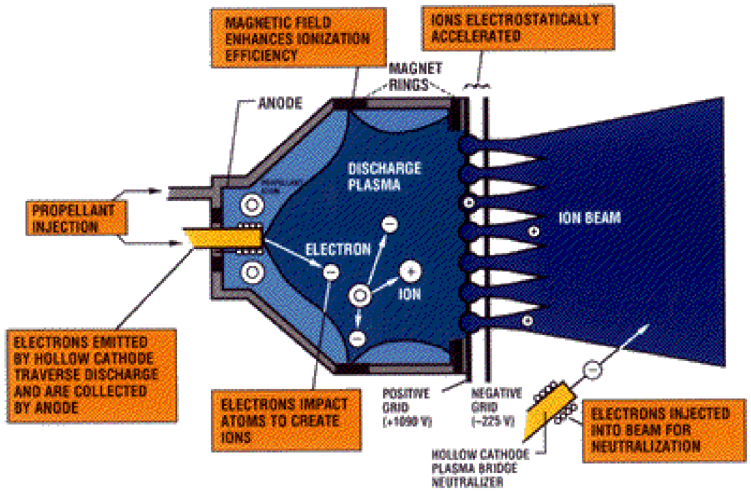


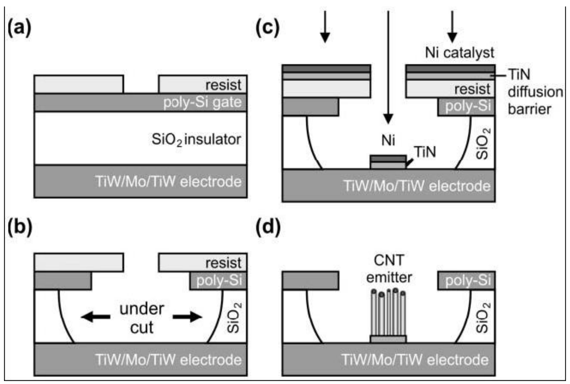
775 C

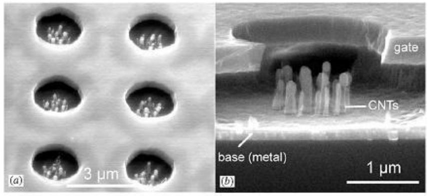


800 C

Ion Electric Propulsion

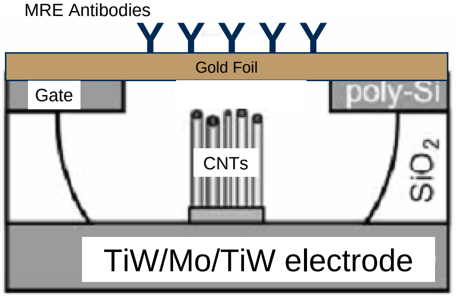


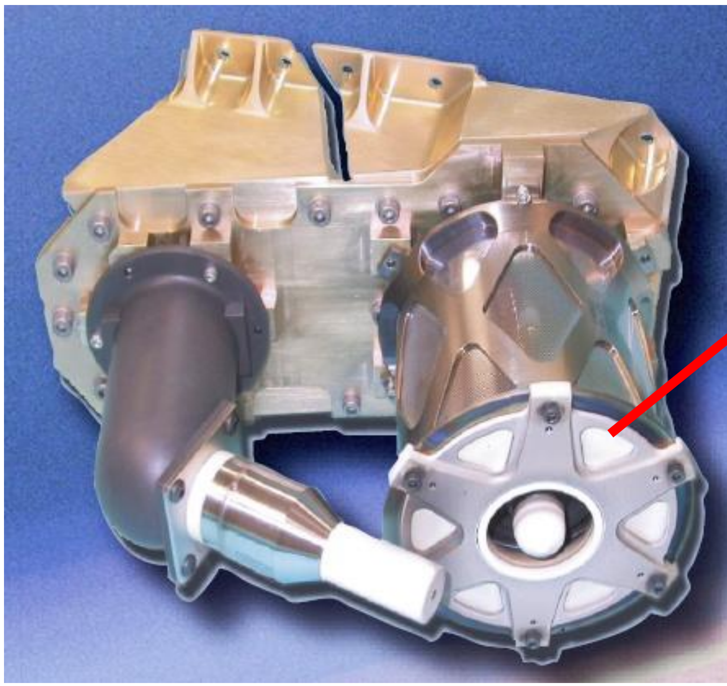


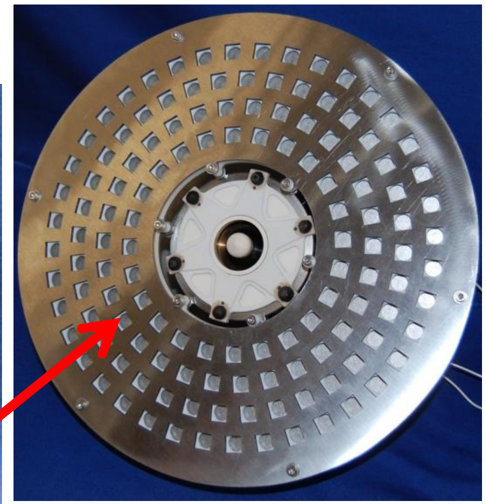


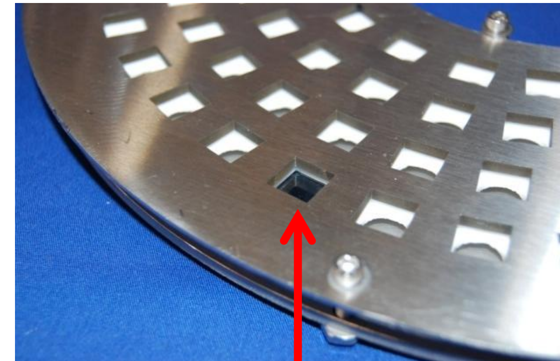
G. Pirio, et al, *Nanotechnology*, vol. 13, pp. 1-4, 2002.

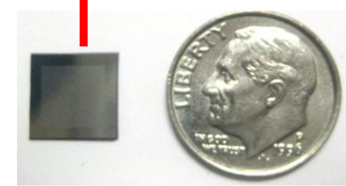
Electron-induced Surface Plasmon Resonance (Chem-Bio Sensor)







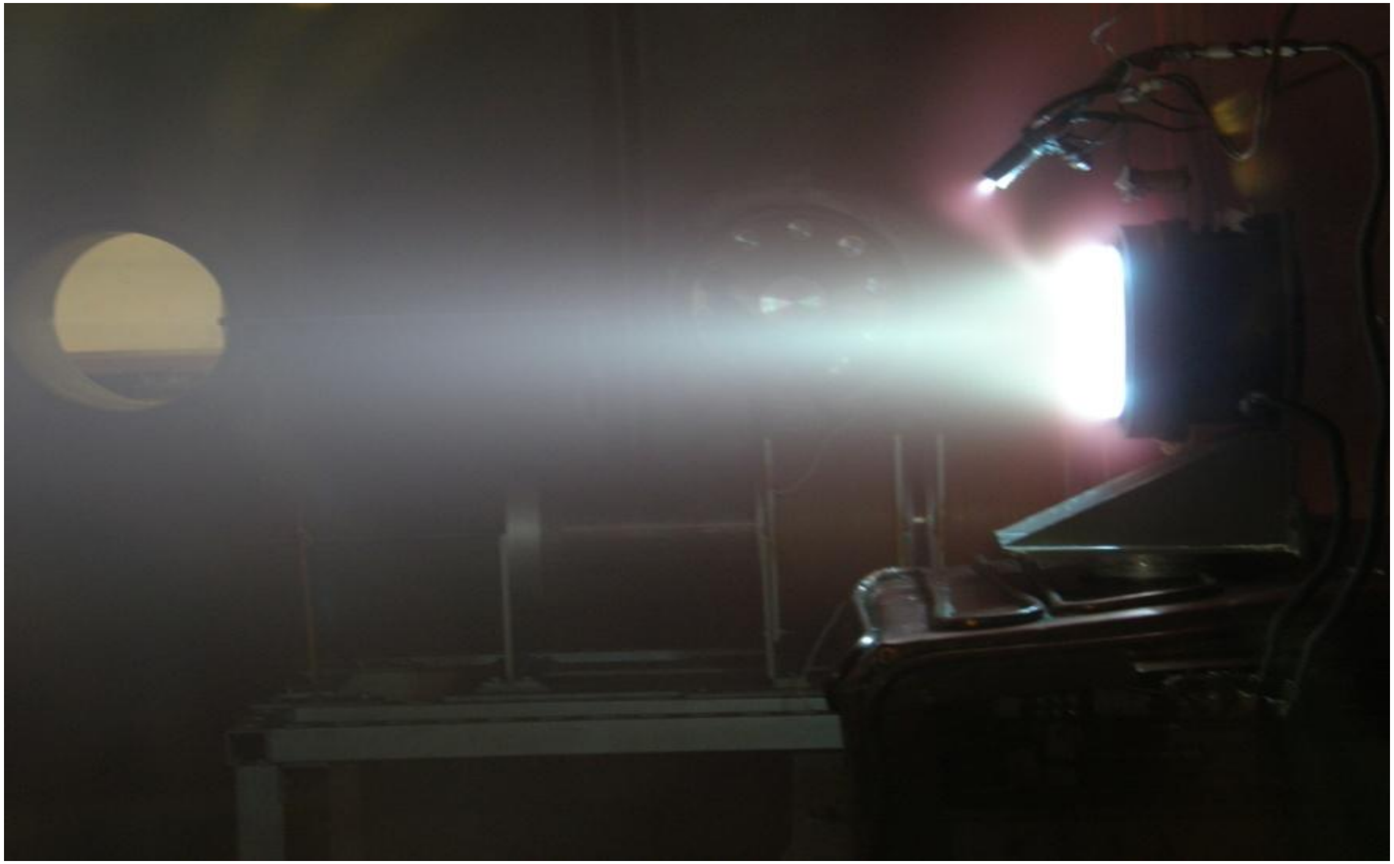




84 Emitter Capacity

2.1 A at 25 mA/cm2

Busek BHT-200 Modified for use with CNT Emitters

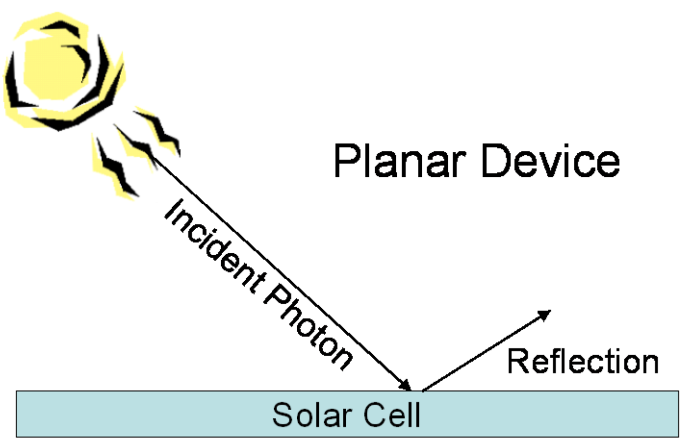


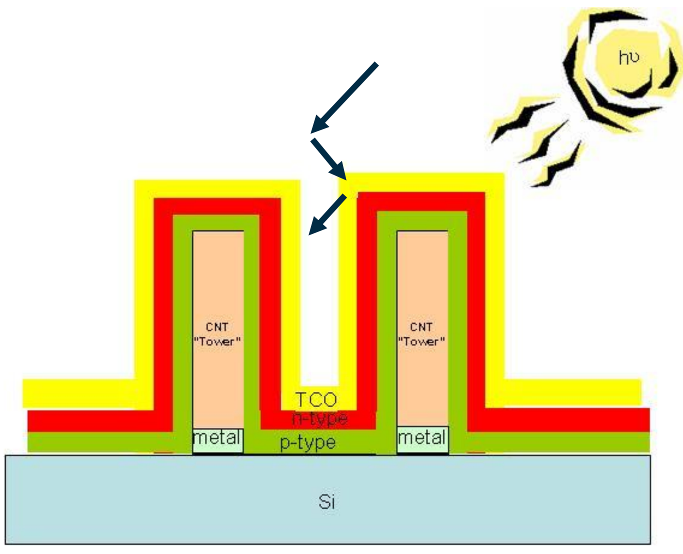
Thrust!

3D Solar Cells

Multiple bounce light trapping

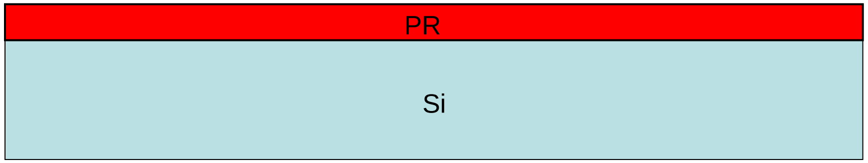
- Light Trapping= more absorbance
- Thinner layers = less recombination
- “orthogonalize” absorption and carrier extraction
- Solves “thick-thin” conundrum





CNT-Based Approach

- PR spun on



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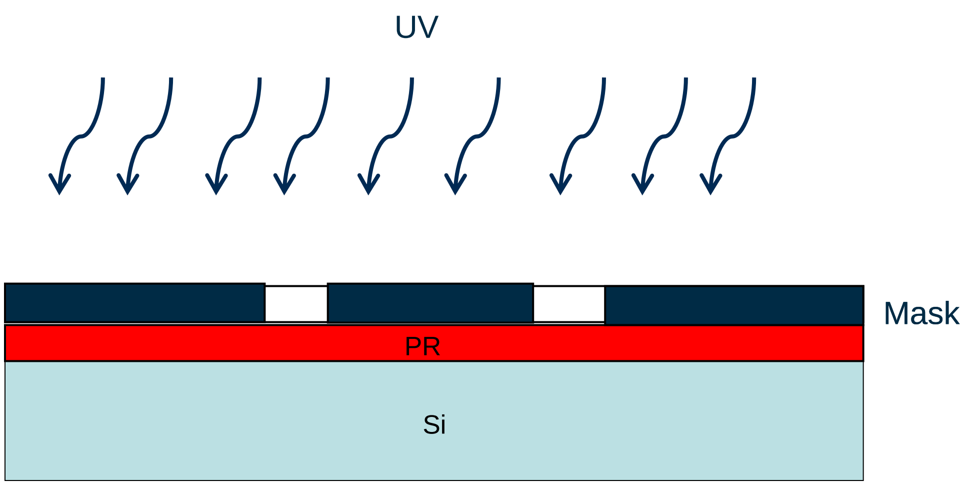
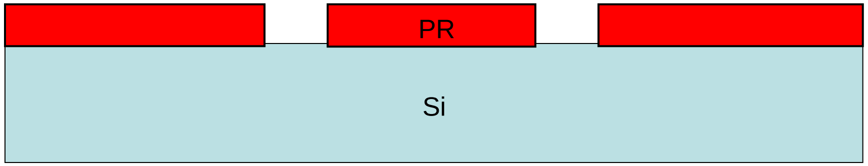


- PR spun on
- Mask and expose to UV

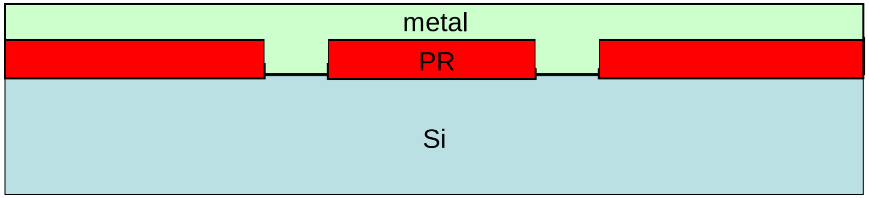
CNT-Based Approach

- PR spun on
- Mask and expose to UV
- Develop PR

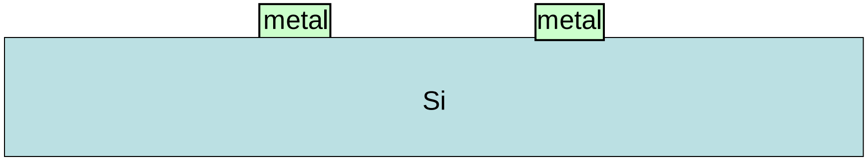


CNT-Based Approach

- PR spun on
- Mask and expose to UV
- Develop PR
- Fe deposited

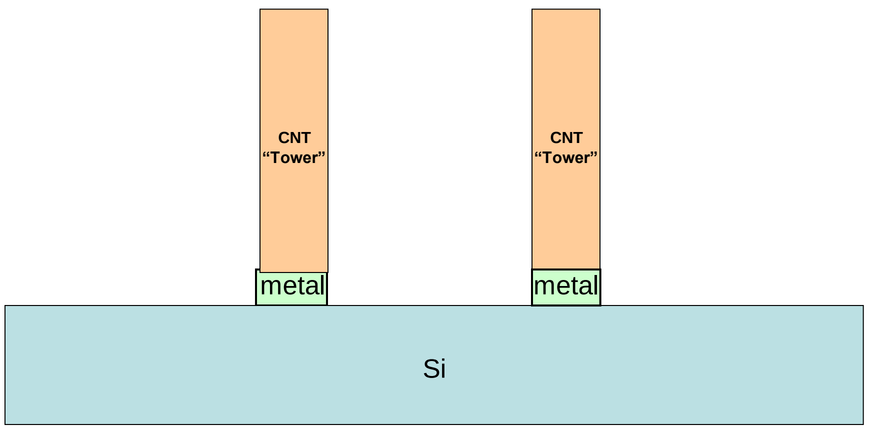


CNT-Based Approach



- Pattern generated on Si substrate via photolithography
- Metal catalyst (Fe) applied
- Lift-off photoresist to leave only patterned catalyst

CNT-Based Approach



- Pattern generated on Si substrate via photolithography
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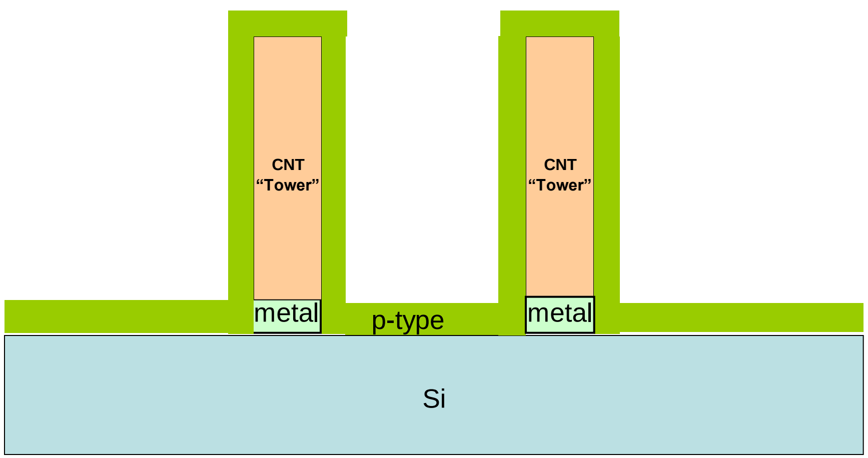
- CNT towers are formed in Chemical Vapor Deposition (CVD) furnace (~720°C; 20 min.)

CNT-Based Approach



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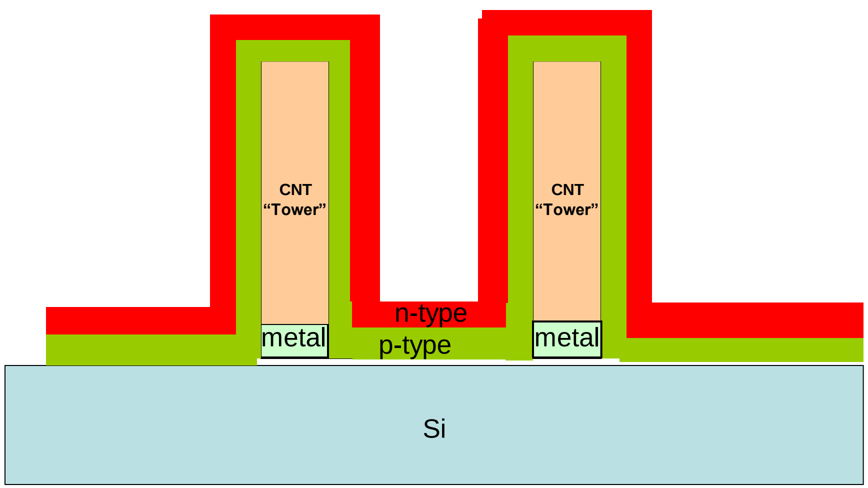
CNT-Based Approach



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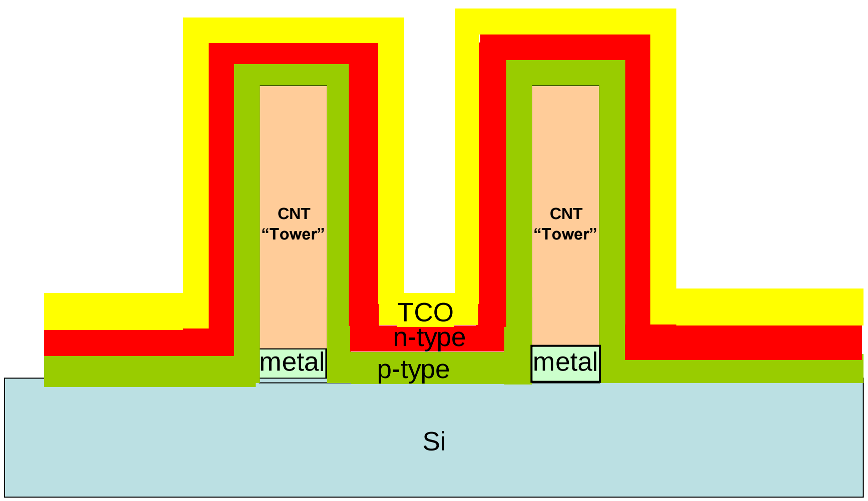
- n-type material (CdS) applied via MBE or CBD

CNT-Based Approach



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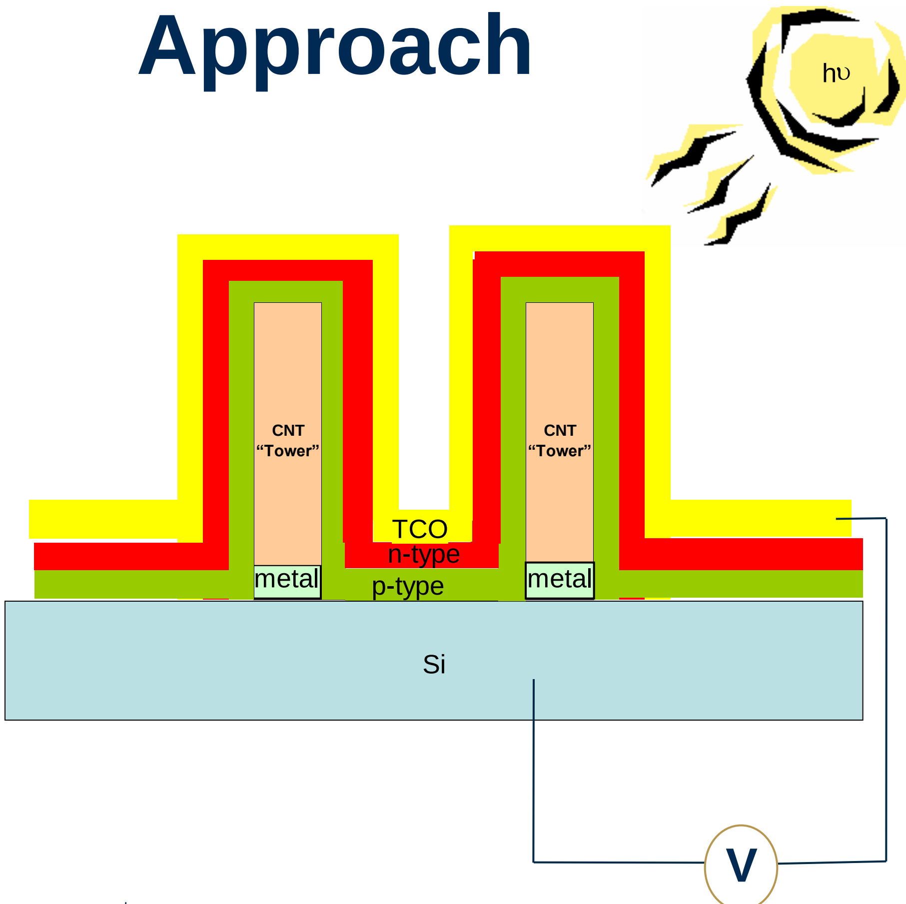
- Transparent Conductive Oxide applied via ion assisted deposition (IAD)

CNT-Based Approach



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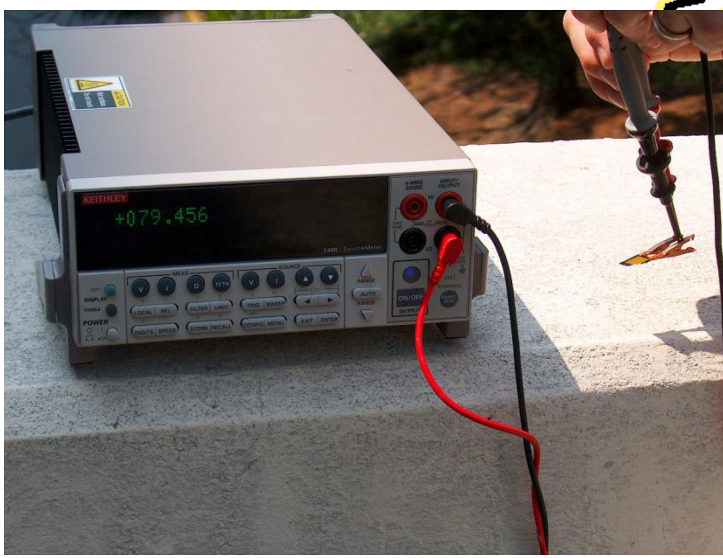

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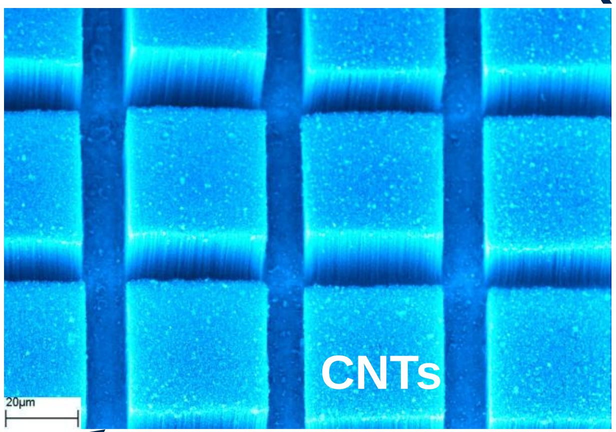
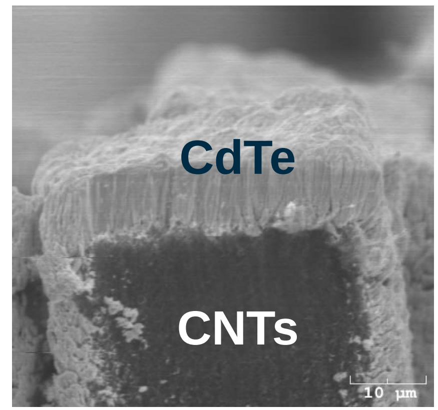
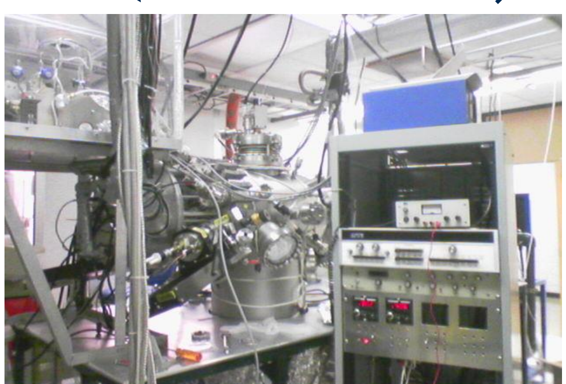
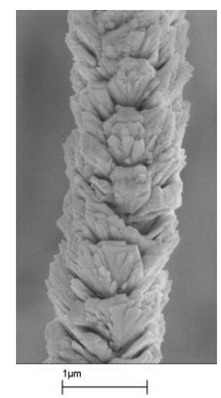
Molecular Beam Epitaxy for CdTe and CdS deposition (p/n junction)

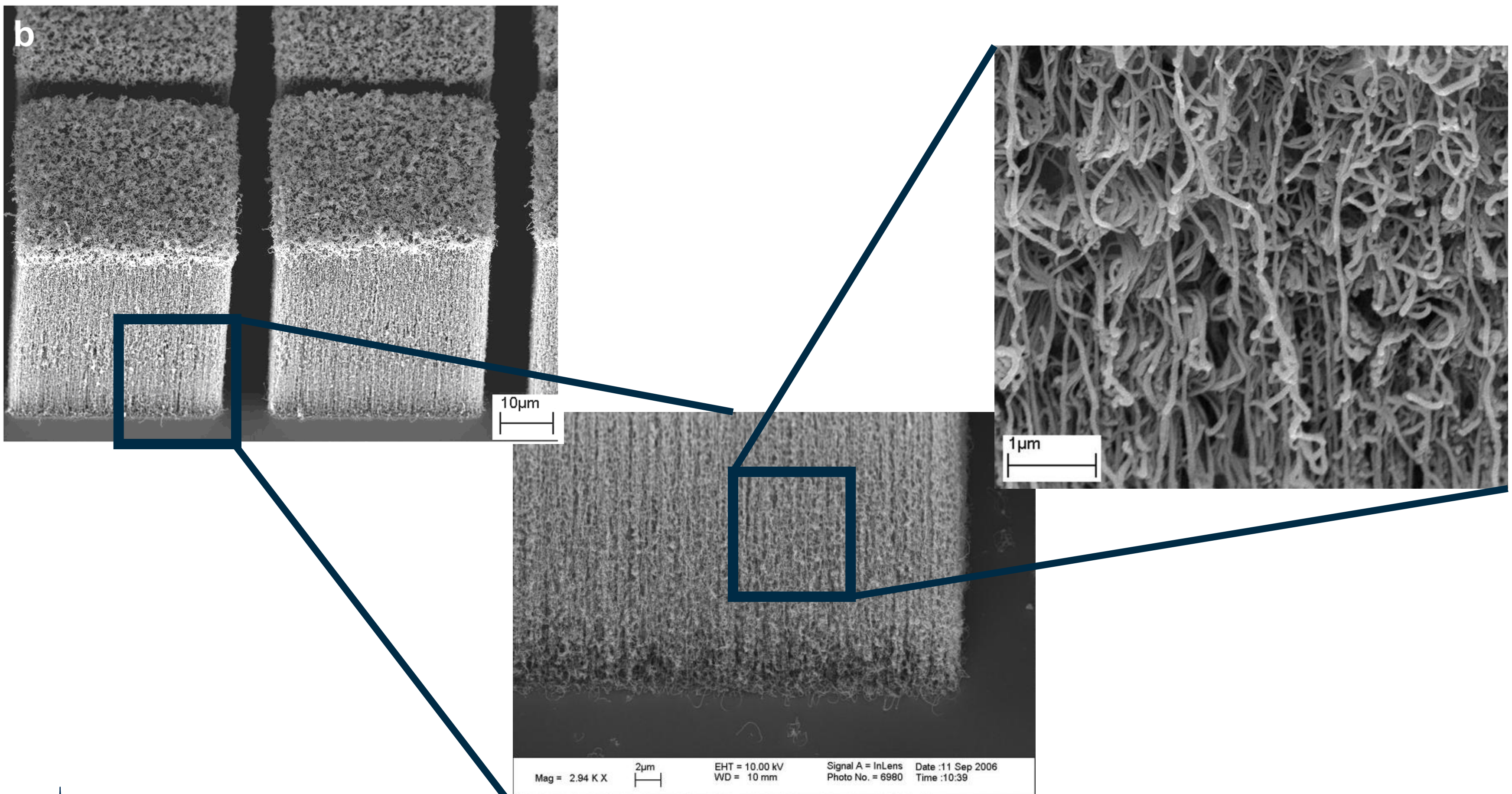


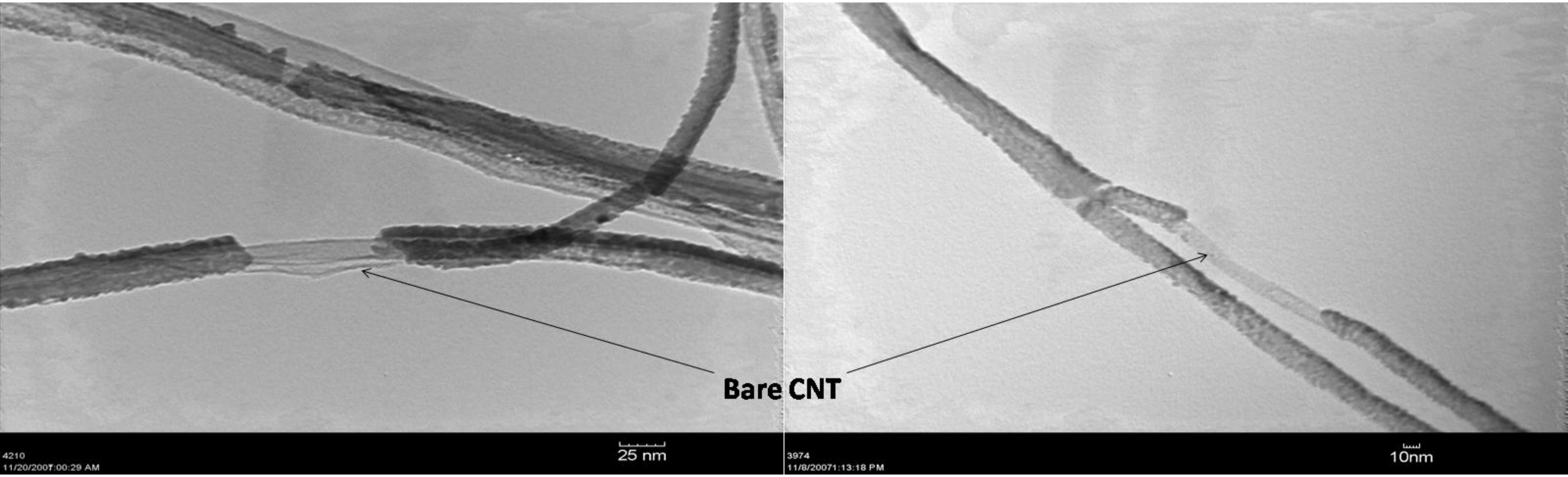
Si substrate



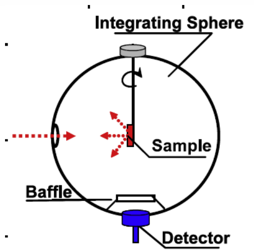


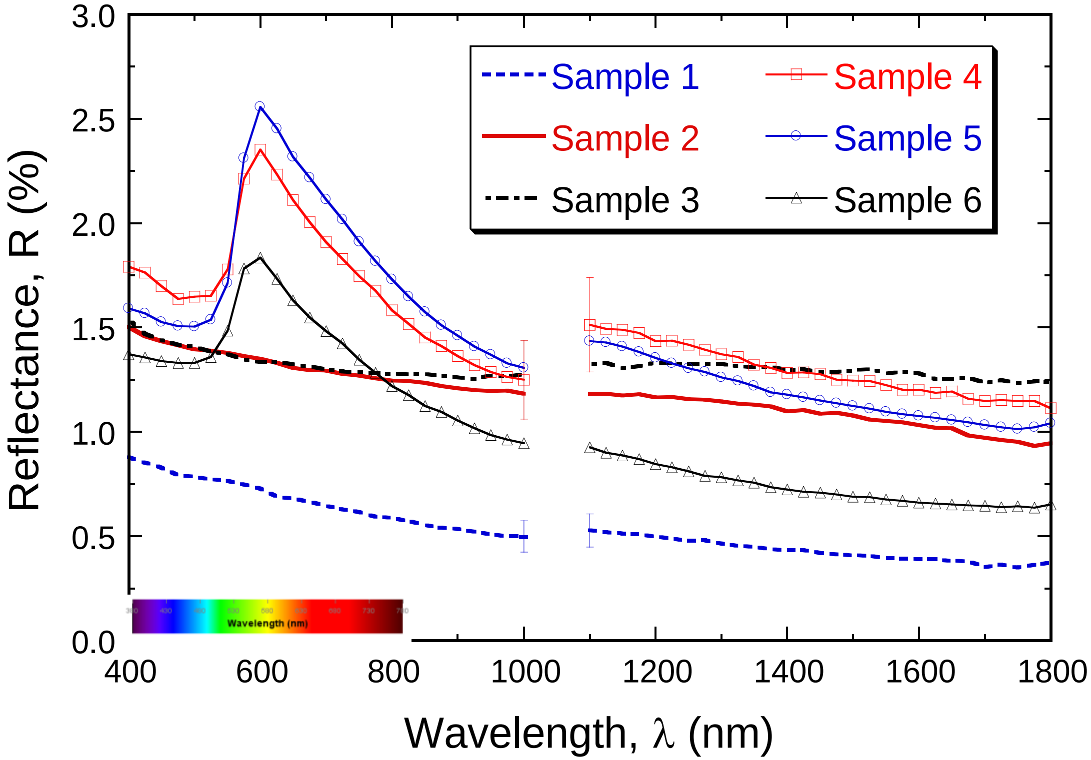


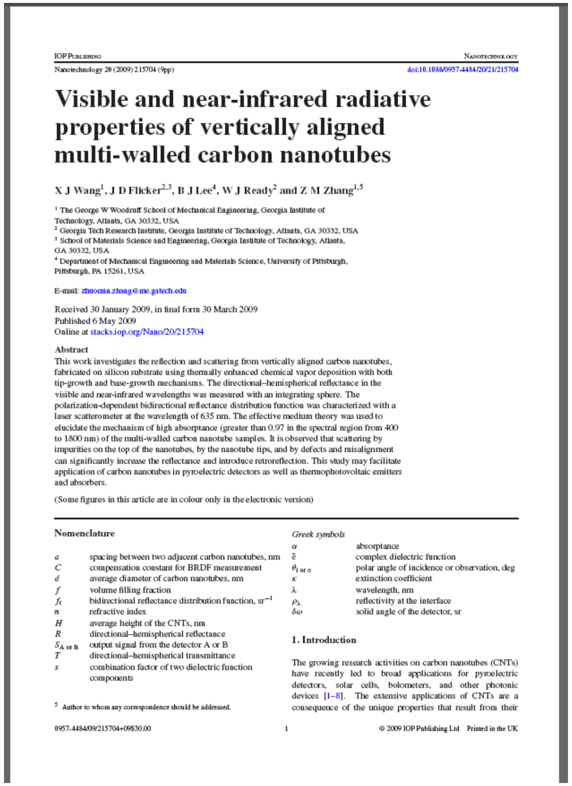

b
10μm
1μm
Mag = 2.94 K X
2μm
EHT = 10.00 kV
WD = 10 mm
Signal A = InLens
Photo No. = 6980
Date :11 Sep 2006
Time :10:39


Bare CNT
4210
11/20/2007 7:00:29 AM
25 nm
3974
11/8/2007 1:13:18 PM
10nm

Light Reflection







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Visible and near-infrared radiative properties of vertically aligned multi-walled carbon nanotubes

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Abstract
This work investigates the reflection and scattering from vertically aligned carbon nanotubes, fabricated on silicon substrate using thermally enhanced chemical vapor deposition with both tip-growth and base-growth mechanisms. The directional–hemispherical reflectance in the visible and near-infrared wavelengths was measured with an integrating sphere. The polarization-dependent bidirectional reflectance distribution function was characterized with a laser scatterometer at the wavelength of 635 nm. The effective medium theory was used to elucidate the mechanism of high absorptance (greater than 0.97 in the spectral region from 400 to 1800 nm) of the multi-walled carbon nanotube samples. It is observed that scattering by impurities on the top of the nanotubes, by the nanotube tips, and by defects and misalignment can significantly increase the reflectance and introduce retroreflection. This study may facilitate application of carbon nanotubes in pyroelectric detectors as well as thermophotovoltaic emitters and absorbers.

(Some figures in this article are in colour only in the electronic version)

Nomenclature

a	spacing between two adjacent carbon nanotubes, nm
C	compensation constant for BRDF measurement
d	average diameter of carbon nanotubes, nm
f	volume filling fraction
f_r	bidirectional reflectance distribution function, sr^{-1}
n	refractive index
H	average height of the CNTs, nm
R	directional–hemispherical reflectance
$S_{A\text{ or }B}$	output signal from the detector A or B
T	directional–hemispherical transmittance
x	combination factor of two dielectric function components

Greek symbols

α	absorptance
$\tilde{\varepsilon}$	complex dielectric function
$\theta_{i\text{ or }o}$	polar angle of incidence or observation, deg
κ	extinction coefficient
λ	wavelength, nm
ρ_λ	reflectivity at the interface
$\delta\omega$	solid angle of the detector, sr

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1. Introduction

The growing research activities on carbon nanotubes (CNTs) have recently led to broad applications for pyroelectric detectors, solar cells, bolometers, and other photonic devices [1–8]. The extensive applications of CNTs are a consequence of the unique properties that result from their

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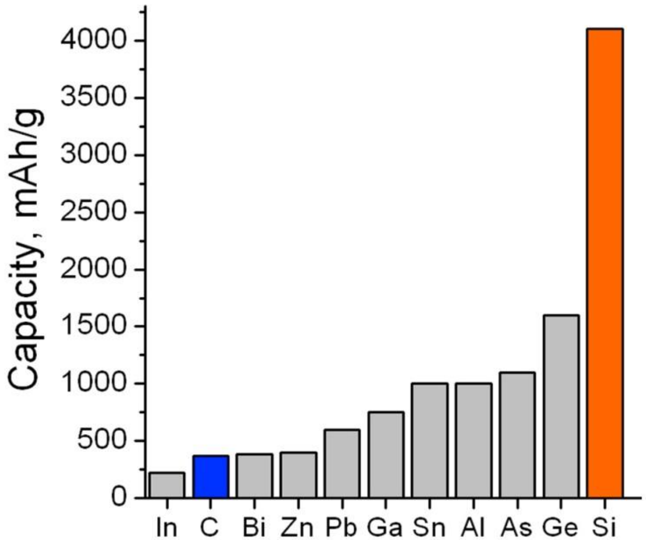
Extra Slides on CNT Batteries

Si-coated Carbon Nanotubes for Li - ion battery anodes

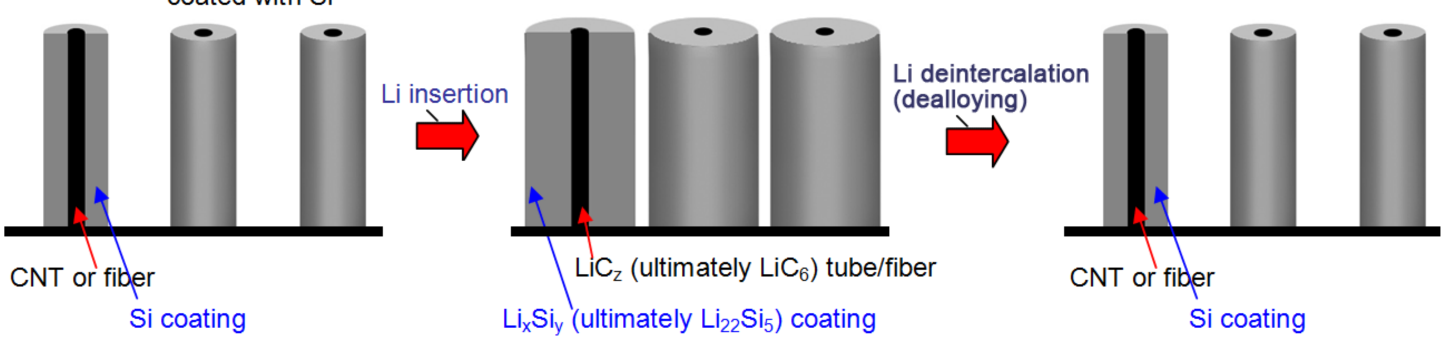
(with Yushin in MSE)

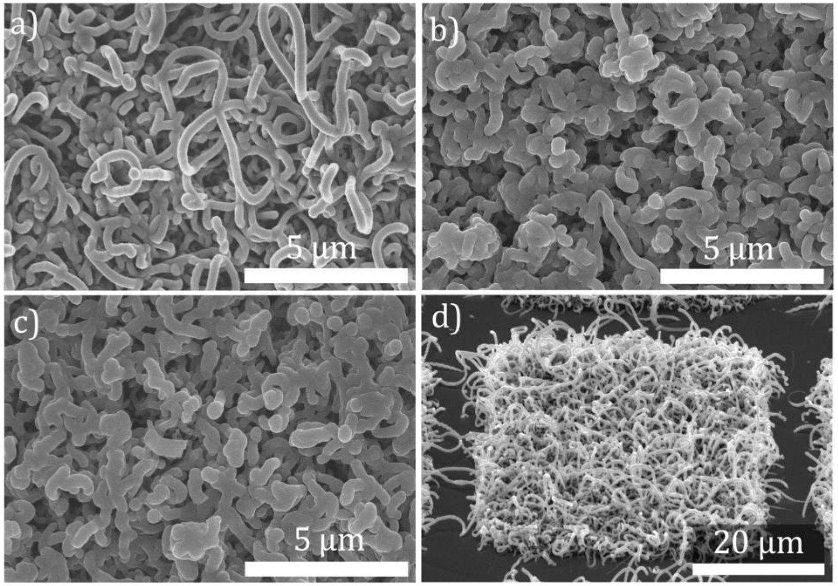


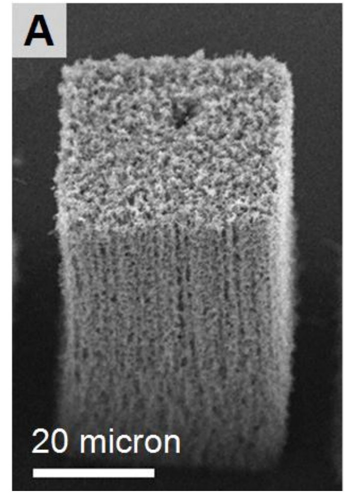
Vertically aligned carbon nanotubes or fibers coated with Si

- **Silicon has an order of magnitude greater capacity compared to graphite anodes**
- **But Silicon has very poor cyclability (pulverizes with Lithium insertion)**
- **Solution = Reinforce Silicon (with Carbon Nanotubes)**

$$Li^+ + e^- + \frac{1}{x}\times\frac{5}{22}\mathrm{Si} \underset{k_a}{\overset{k_c}{\rightleftarrows}} \frac{1}{x}\times Li_xSi_{\frac{5}{22}}$$

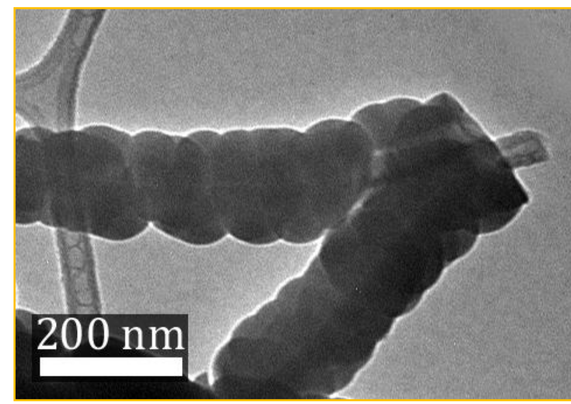




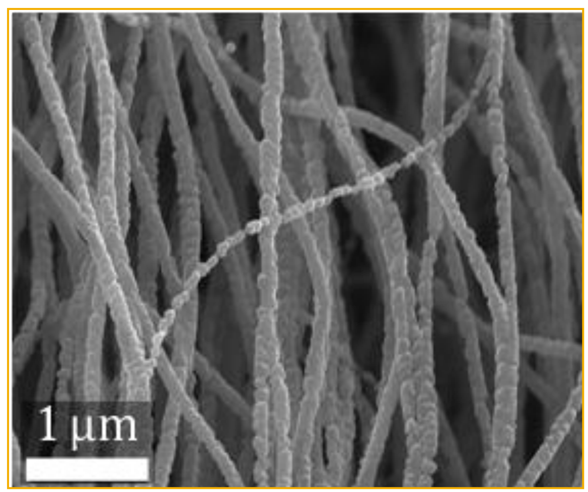


Vertically aligned carbon nanotubes

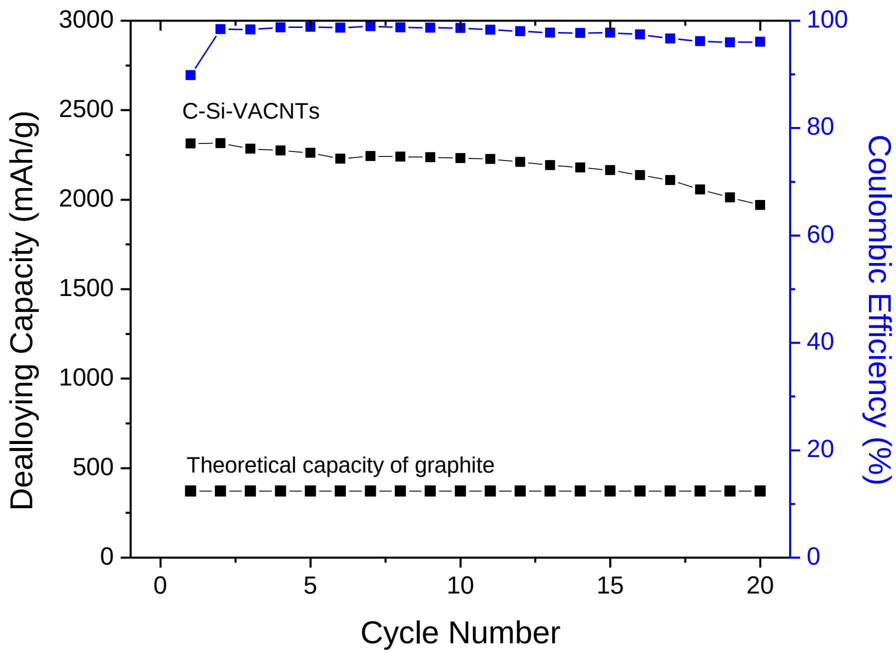
Act as "rebar" to strengthen internal structure of Si-battery



Pictures of Si-coated Carbon Nanotubes Demonstrates conformal coatings are possible



Charge/Discharge Results



- **Stable performance and reversible dealloying capacity in excess of 2000 mAh/g (over 5x more than graphite) has been demonstrated.**
- **VACNTs provide structural support for Si as well as dramatically improved electrical conductivity therefore higher power Si-containing electrodes are possible.**

Patterned & Aligned CNTs

- Sensors
- Cultures
- Scaffolds
- Heat Sink
- Batteries
- Fuel Cells
- Logic circuits
- Hydrogen storage
- Waveguide/Filter
- Many, MANY more . . .