Carbon Nanotube Switches for Communication and Memory Applications

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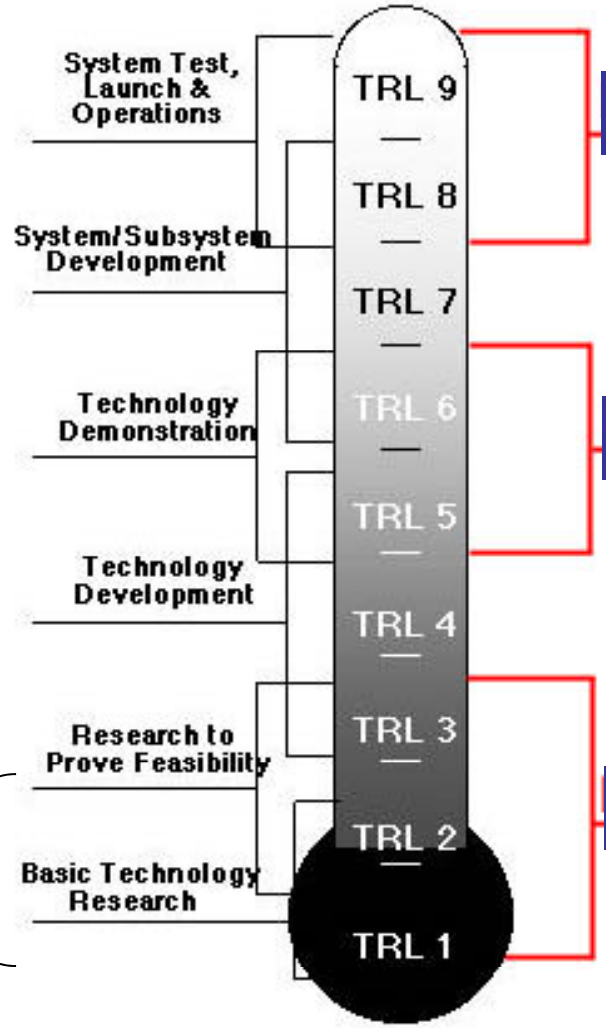
NASA Technology Development



Flight technologies

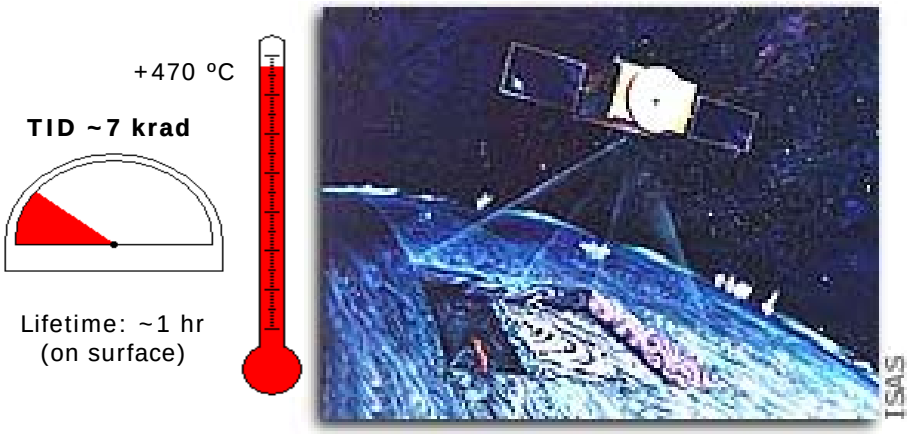
Mid-level technologies

Early level technologies

This work on CNT switches

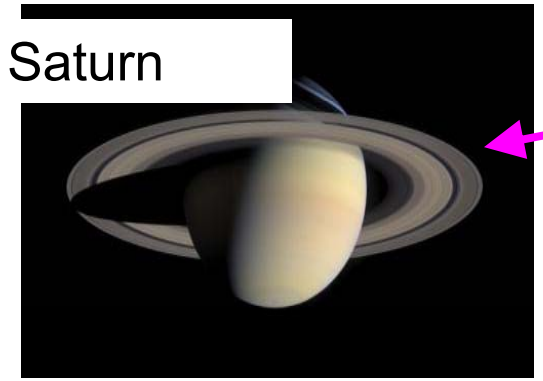
Applications: Extreme Environments

Venus planetary probe mission



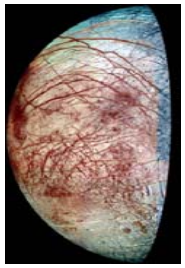
- Extreme environment electronics (temperature, radiation, chemical, etc)

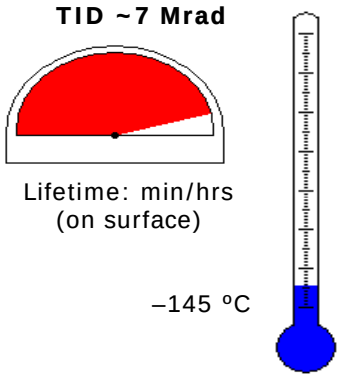
Titan and Europa Missions



Titan

Europa





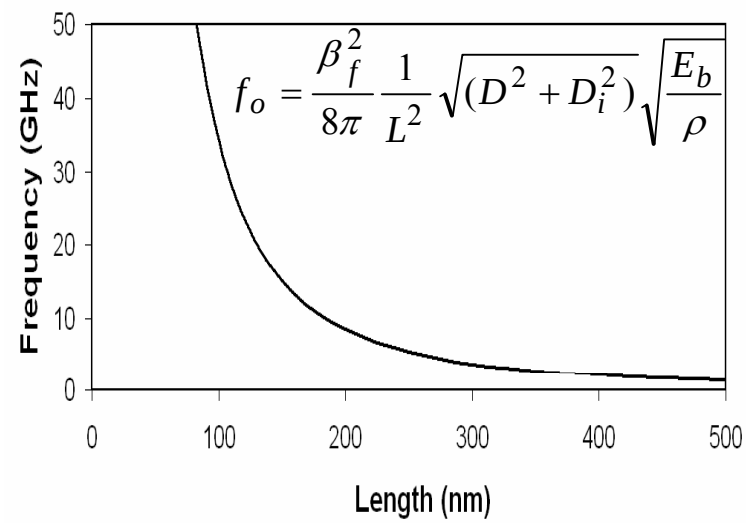
CNTs for Switching Applications

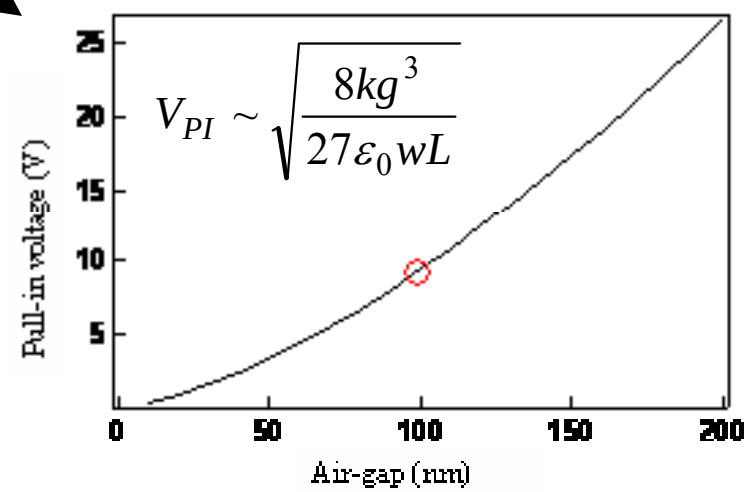
CNT Material Properties

- High elastic modulus (TPa)
- Structurally hollow and massless
- Intrinsically nanometer scale dimensions
- Accommodates large strains (~ 11%)
- Thermally stable (high conductivity ~ 6000 W/Km)
- Radiation tolerant

Expected Device Characteristics

- High switching speeds (~ ns)
- Low actuation voltages (< 10 V)
- Fatigue related failure minimized
- Operable in space applications without shielding

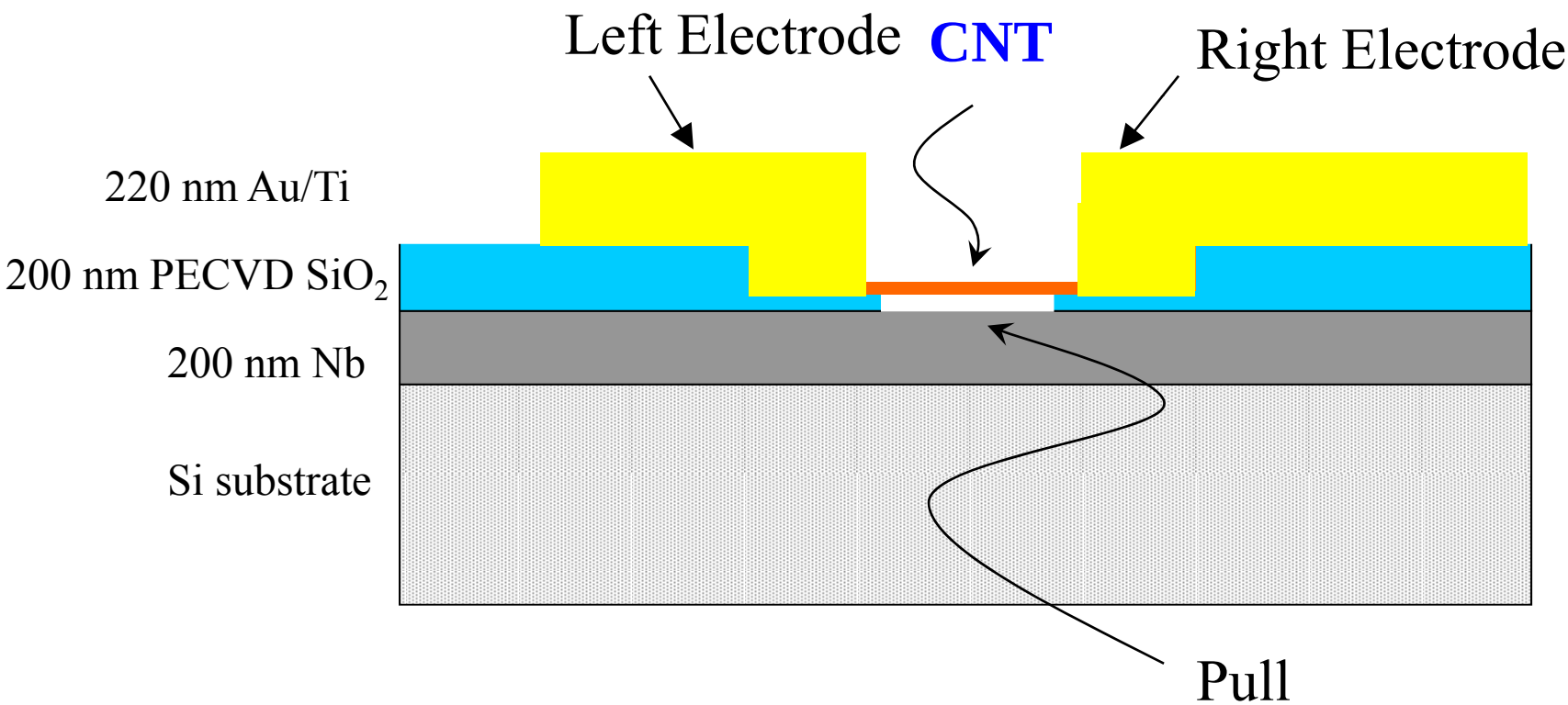




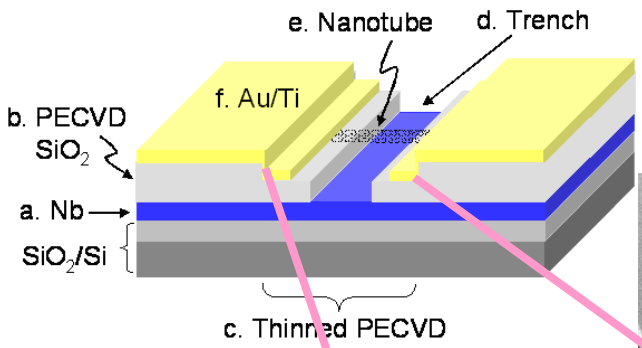
Lateral Air Bridge Switches

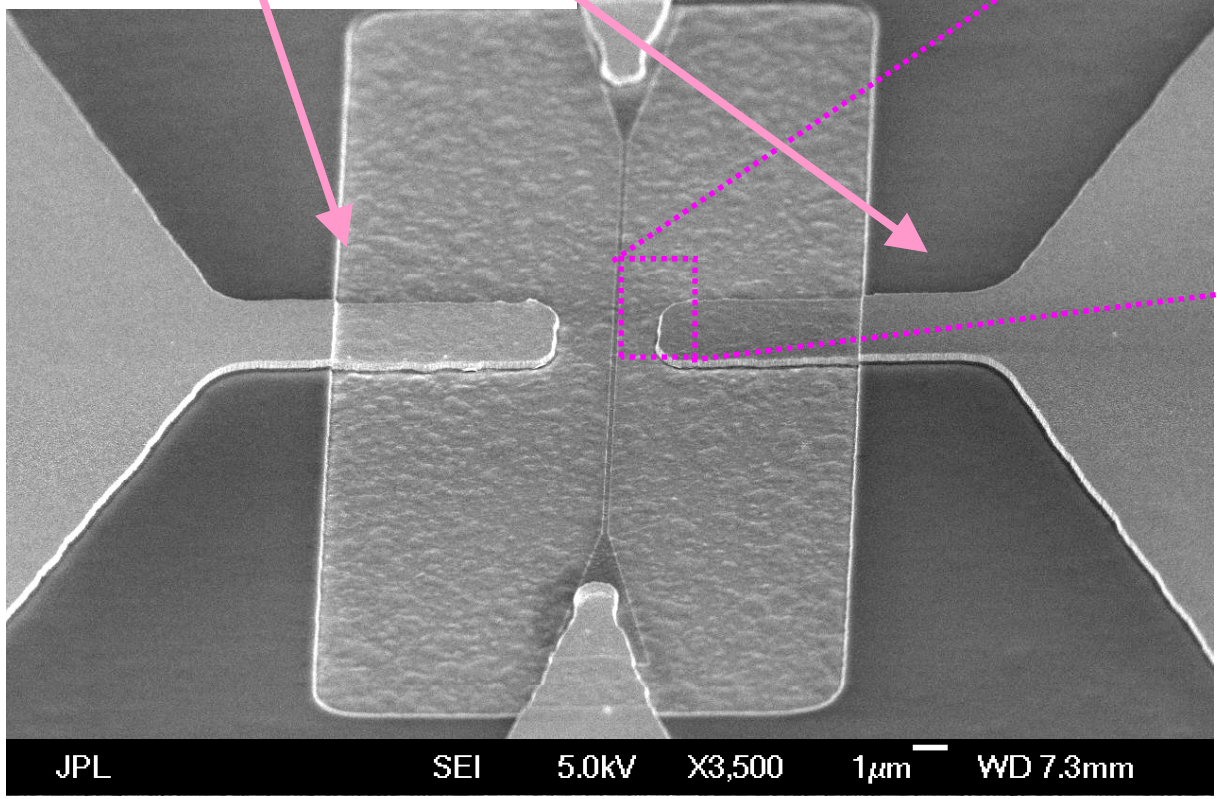
Air-bridge formation process

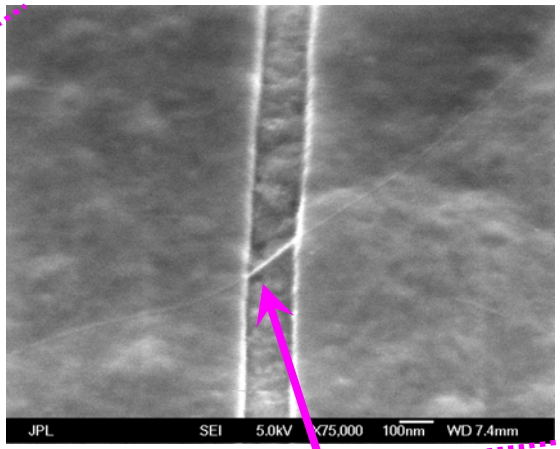
(1) Contact made to a pre-deposited Nb ground plane
(2) Deposited intermetal dielectric: PECVD SiO_2



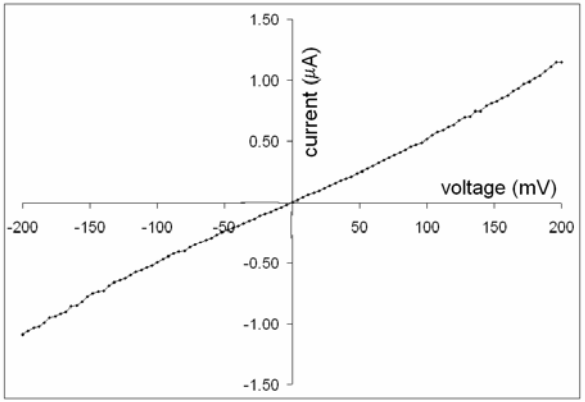
SEM of Fabricated Devices



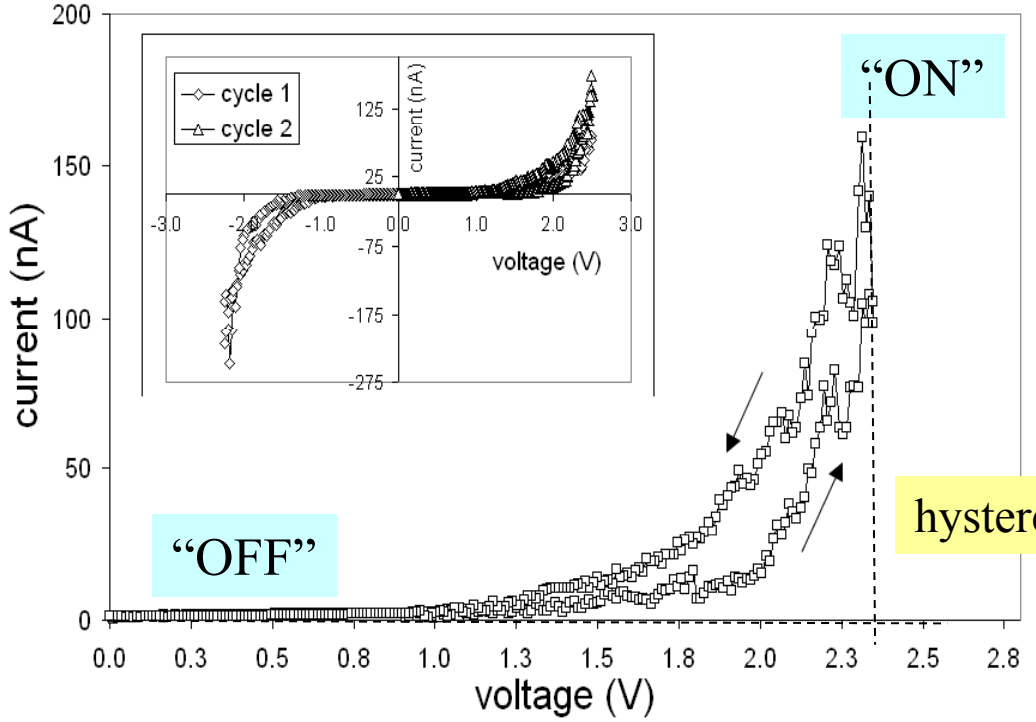




CNT bridging trench

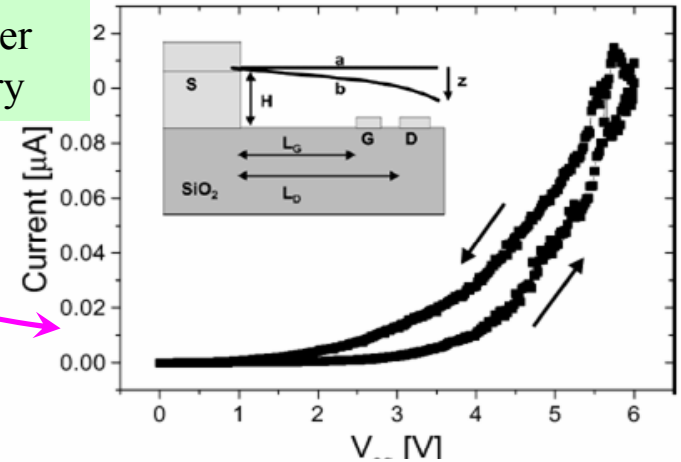


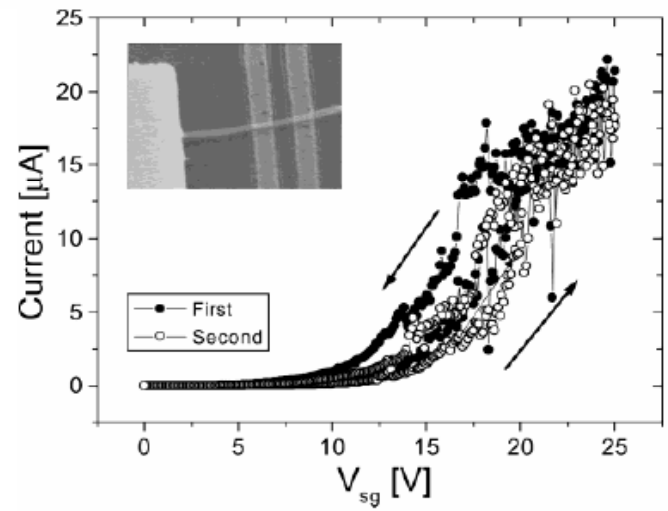
DC Measurements



deposited MWNT cantilever geometry

S. W. Lee, E. Campbell, *et. al*, *Nano Lett.* **4**, 2027 (2004)



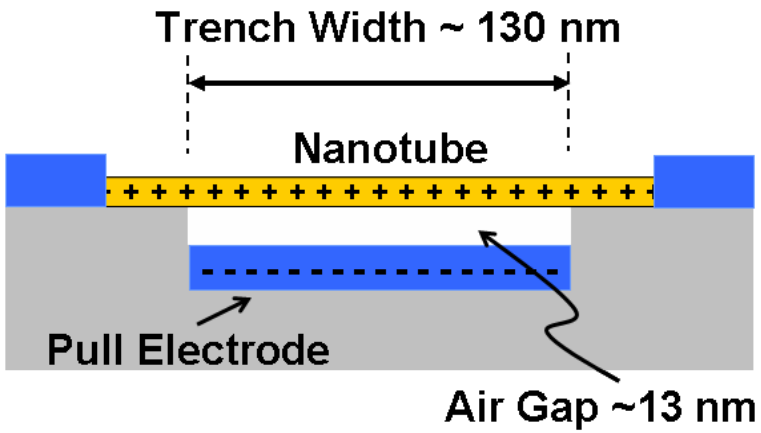


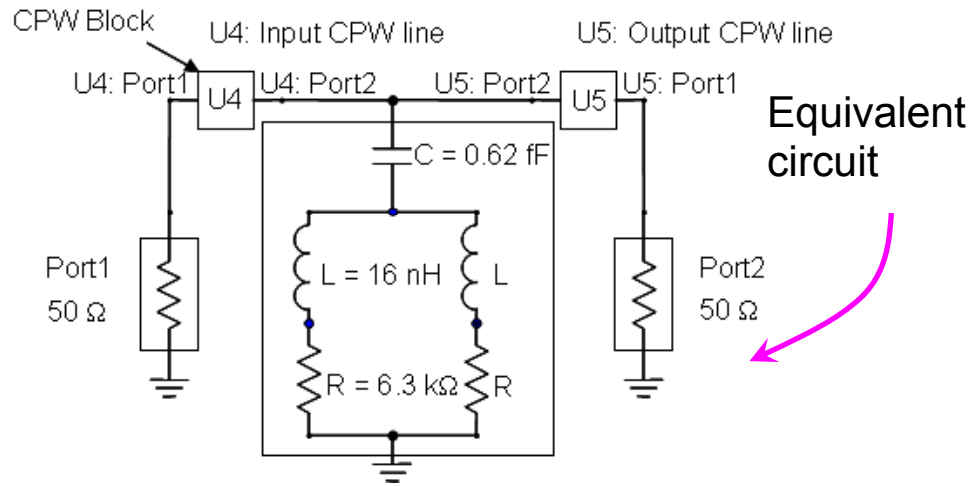
- Switching is polarity independent: rules out field emission
- Low actuation voltages (few volts)
- Power dissipated ~ 500 nW per switching event

A. B. Kaul, E. W. Wong, L. Epp and B. Hunt, *Nano Lett.* 6 (2006)

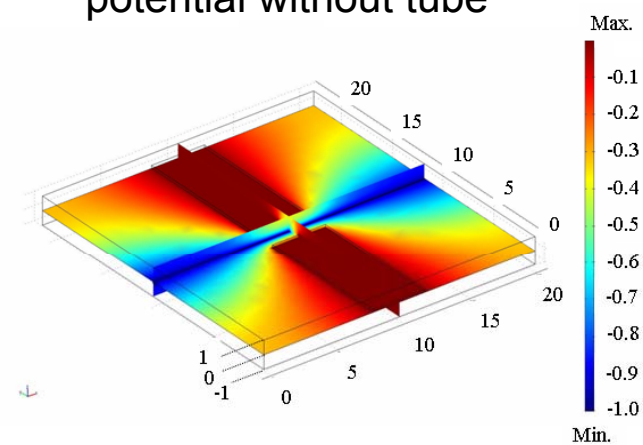
RF Simulations of Air-Bridge Switch
(Shunt Configuration)

Jet Propulsion Laboratory
California Institute of Technology

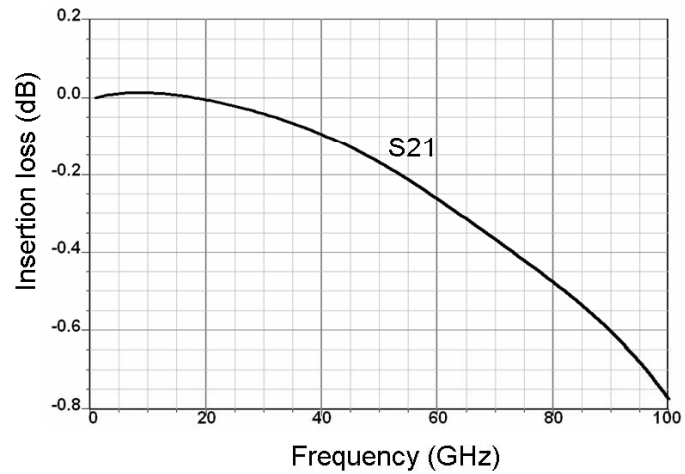




FEMLAB solution of electric potential without tube

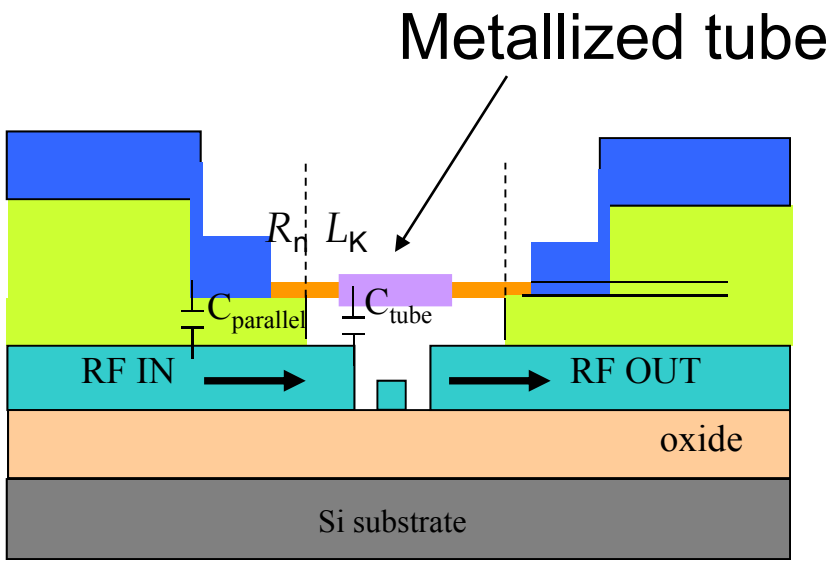


Stray capacitance only ~ 420 aF!
With tube ~ 623 aF

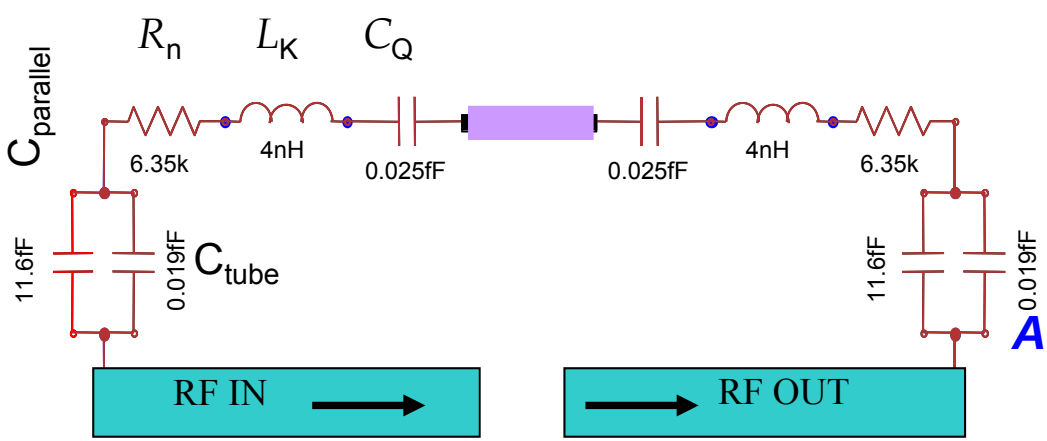


- Less than 0.8 dB insertion loss up to 100 GHz
- Expect good high frequency response of switch in "open" or "up" state; **but isolation is poor in "closed" or "down" state!**

RF Simulations of Air-Bridge Switch
(Series Configuration)



Equivalent Circuit



Nanotube capacitance over RF lines

- Approximate analytical solution:

  $C_{tube} \approx 2\pi\varepsilon\ell / \ln(h/R)$, in air

  - h = 20 nm
  - R = 1.0 nm
  - $\ell \approx 1000$ nm (approximate)

Analytic Nanotube Capacitance:

C_{tube} = 18.6 aF = 0.019 fF

Parallel capacitance on SiO_2 over RF lines

- Approximate analytical solution:

  $C_{parallel} \approx \varepsilon(\ell w) / d$, in SiO_2

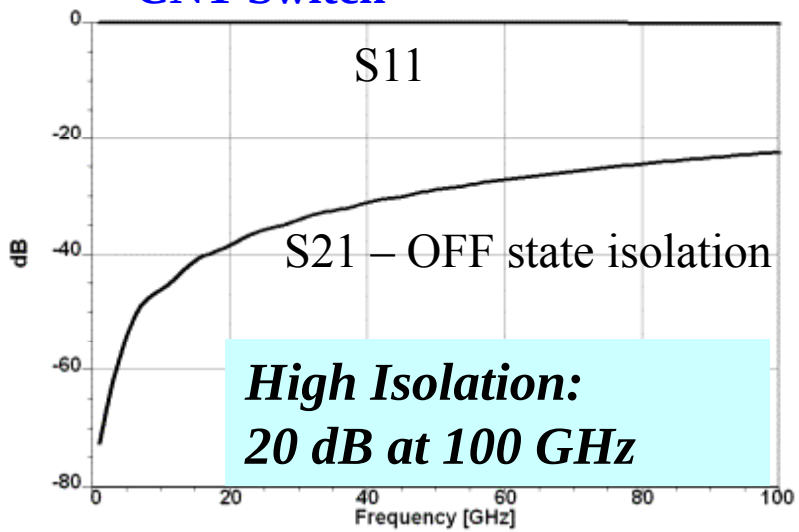
  - ℓ = 250 nm
  - w = 250 nm
  - d ≈ 20 nm

Analytic Parallel Plate Capacitance:

$C_{parallel}$ = 11.6 fF

CNT RF Switch up to 100 GHz

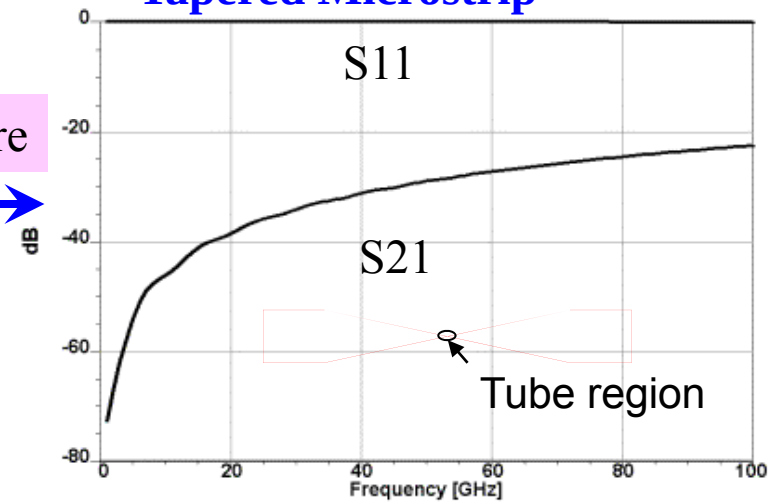
CNT Switch

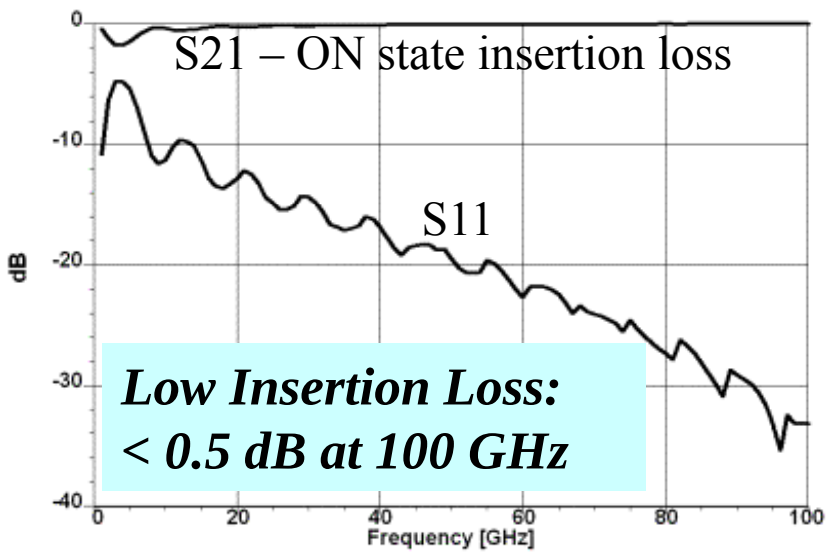


High Isolation:
20 dB at 100 GHz

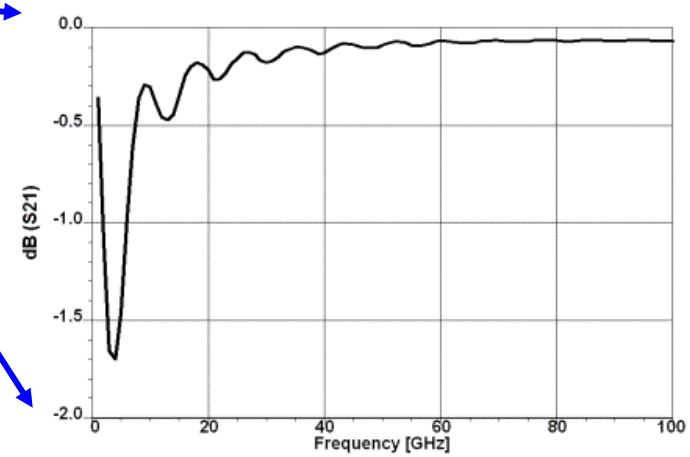
Compare

Tapered Microstrip





Low Insertion Loss:
< 0.5 dB at 100 GHz



Attributes of CNT RF Switch

Advantages

- Limited metallization of tube needed:
  - maintains high spring constant, so high speed
  - tube resistance (R_n) and inductance (L_K) decrease coupling through tube in off-state resulting in high isolation
- Even if Si MEMS switches scaled to nm scale dimensions using heroic lithography, parasitics will limit RF performance

Potential Applications

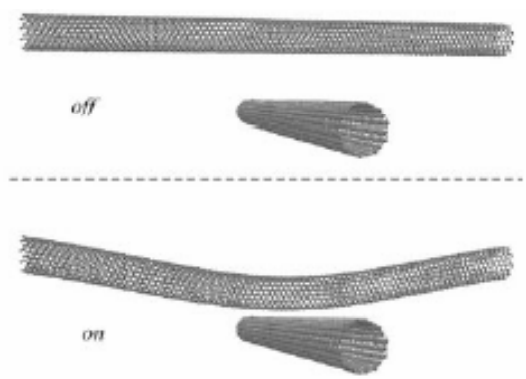
- DC CNT switch **demonstrated** to have high speed, low voltage and low power dissipation
- **Simulated** RF CNT switch exhibits low loss and high isolation up to 100 GHz
- Combined attributes of DC and RF CNT switch should be of extreme value for communication systems (phase shifters, phased array antennas, RF front-end transceivers)

Vertical Switches
(Memory Applications)

An application of CNTs for Memory

P. Kim *et al. Science*, **286** (1999) (nanotweezers)
P. Poncharal *et al. Science,* **283** (1999) (resonators)
T. Rueckes *et al. Science*, **289** (2000) (nonvolatile memory)

CNT memory



Energy Equation

$$E_{Total} = E_{elast} + E_{electro} + E_{vdW}$$

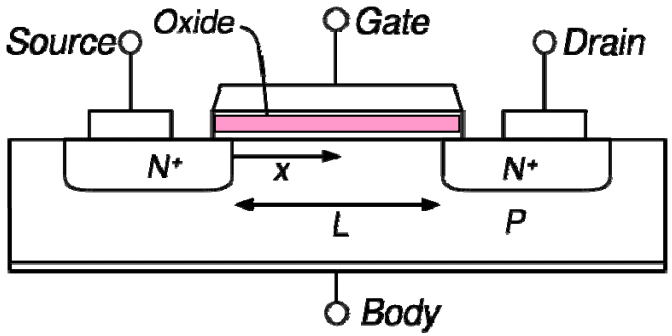
CNT Memory

- information retained at zero power dissipation
- enhanced radiation tolerance

Semiconductor Memory

- charge sensitive device (capacitive), leakage, suseptible to radiation
- SRAM, DRAM volatile, need to be refreshed, consuming power

Semiconductor Memory



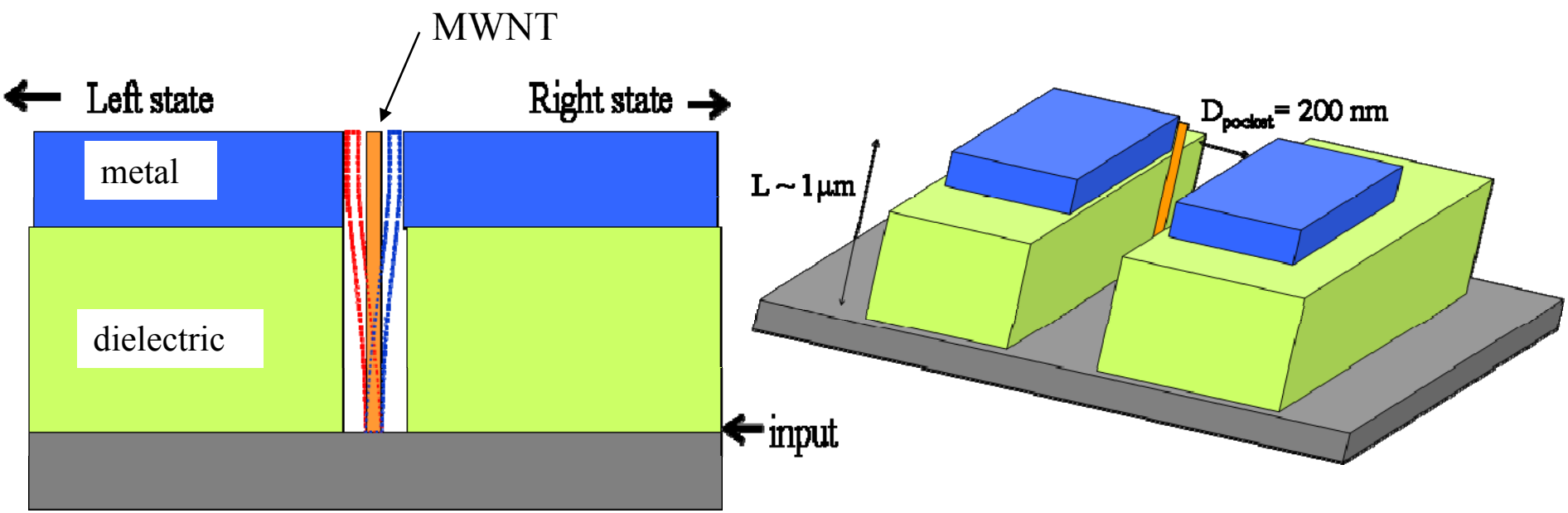
Comparison to "benchmark"

Type / Figure of Merit	SRAM	DRAM	Flash	CNT switch (potential)
Switching Speed	Very high (~ ns) ✓	High (few ns – 10's ns)	Low (> μs)	Very High (~ ns) ✓
Power	High (< few W)	Medium (< 100's mW)	Very Low (< 1 μW) ✓	Very Low (< 1 μW) ✓
Cost	High	Very Low ✓	Low	Very Low ✓
Non-volatile	No	No	Yes ✓	Yes ✓
Cell-size	Large (~ 6 Transistors)	Small (1 Transistor) ✓	Large (> few Transistors)	Very Small ✓
Write-cycle lifetime	High (~ 10^{15} cycles) ✓	High (~ 10^{15} cycles) ✓	Low (~ 10^{4} cycles)	High (~ 10^{15} cycles) ✓

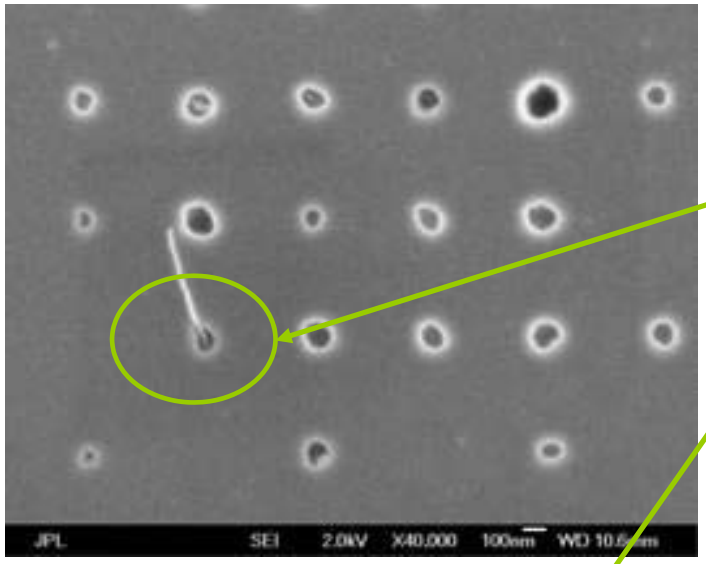
Potential for "universal stand-alone" memory

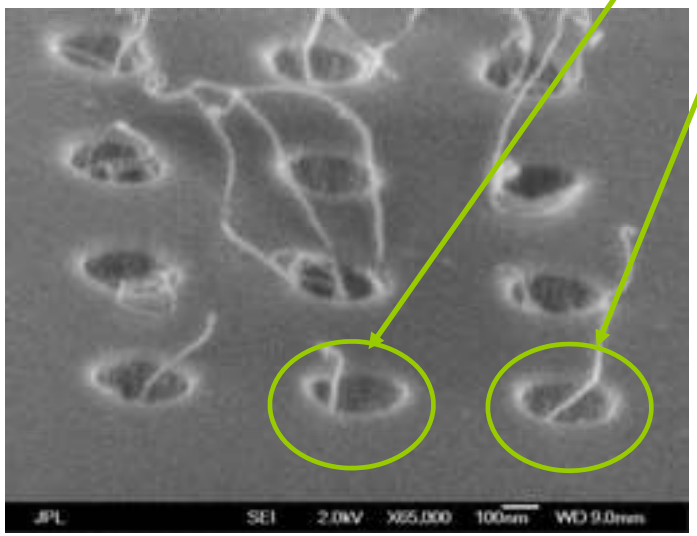
Vertical CNT Switch

- Tubes are grown perpendicular to the substrate
- 3D Electronics: enables switching between layers
- High density design
- Other electrode can be used to de-actuate



CNT Growth from Deep Nano-Pockets





Growth on SiO_2 substrate

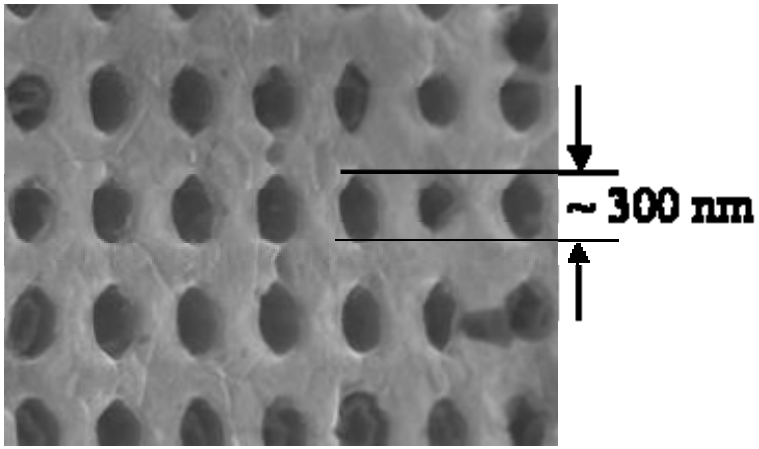
- MWNTs grown from isolated holes in ~ 1 μm deep SiO_2 pockets
- 575 C, 200 Torr ethylene, 2 min.
- Growth rate ~ 0.75 um/min rate
- CNTs protrude out of holes by 100-1000 nm

Growth on conducting substrate

- Verified that CNTs can grow directly on heavily doped-Si
  - Fe/Al (2.5 nm/3.0 nm)
  - Al inhibits Fe alloying with Si at high growth temperatures

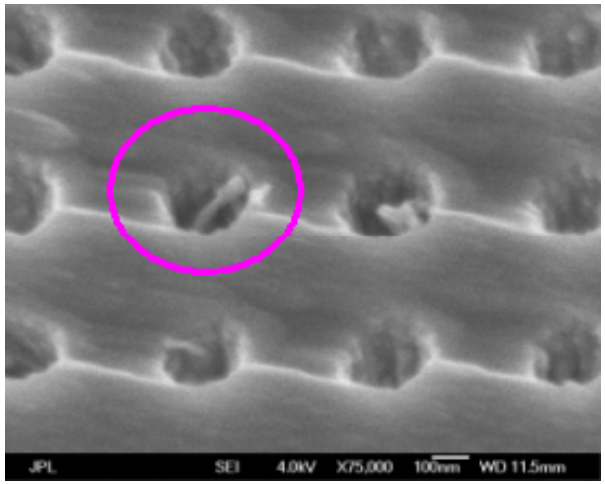
Formation of deep Nanopockets

Formation of deep nano-pockets



- E-beam resists poor etch resistance
- E-beam pattern transfer into Al hard mask using ICP etch
- Etch deep into SiO_2 using fluorine chemistry

Trimming CNTs



- Grazing angle ion mill to trim CNTs
- ~ 10 deg., 350 eV Ar+ ions, 15 min.

Growth of aligned vertical MWNTs

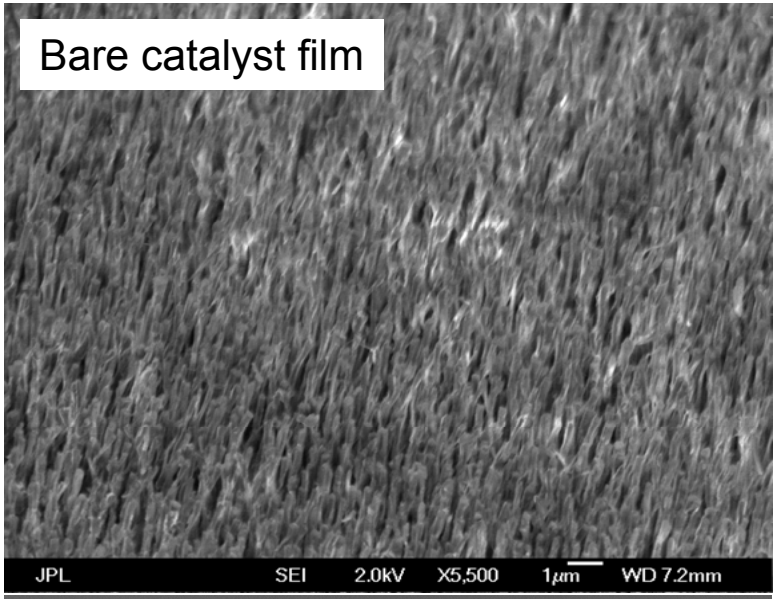
Thermal CVD

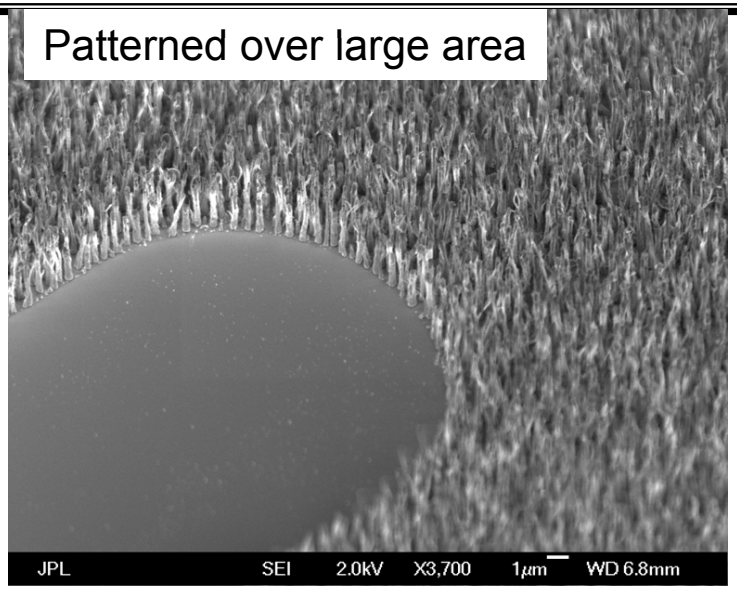
- In absense of E-field, thin film catalyst nucleates growth of “mats of CNTs” at 600 – 700 ºC
- In PECVD induced dipole of the tubes aligns to the external E-field
- Results in vertically aligned arrays of CNTs

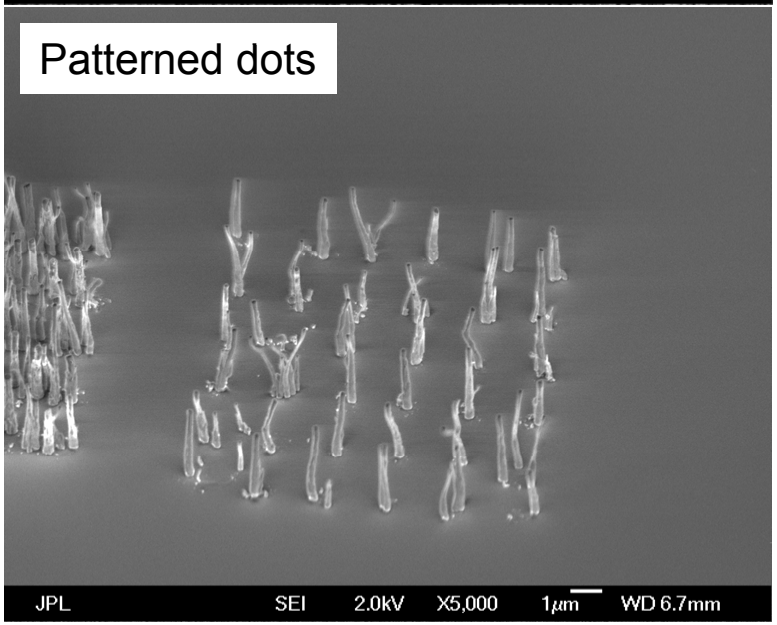
PECVD Growth Characteristics Used

- Gas Mixtures used: C_2H_2 and NH_3
- Growth temperature ~ 700 ºC
- Electrode spacing ~ 8 mm
- Catalyst used was Ni
- CNT growth extremely sensitive to thickness of catalyst layer

PECVD Growth of CNTs







- Tip-growth mechanism observed in vertical arrays of MWNTs
- Single-few tubes result by controlling size of catalyst “dots” (100’s nm diameter)
- Patterning of Ni catalyst performed with optical lithography
- Switch device development efforts are in progress

Summary and Future Work

Lateral CNT Switches

• dc CNT switches were demonstrated to operate at low voltages, low powers and high speeds

• RF simulations of switch in series configuration with metallized tube yielded good RF performance

- Isolation simulated to be ~ 20 dB at 100 GHz
- Insertion loss simulated to be < 0.5 dB at 100 GHz

Vertical CNT Switches

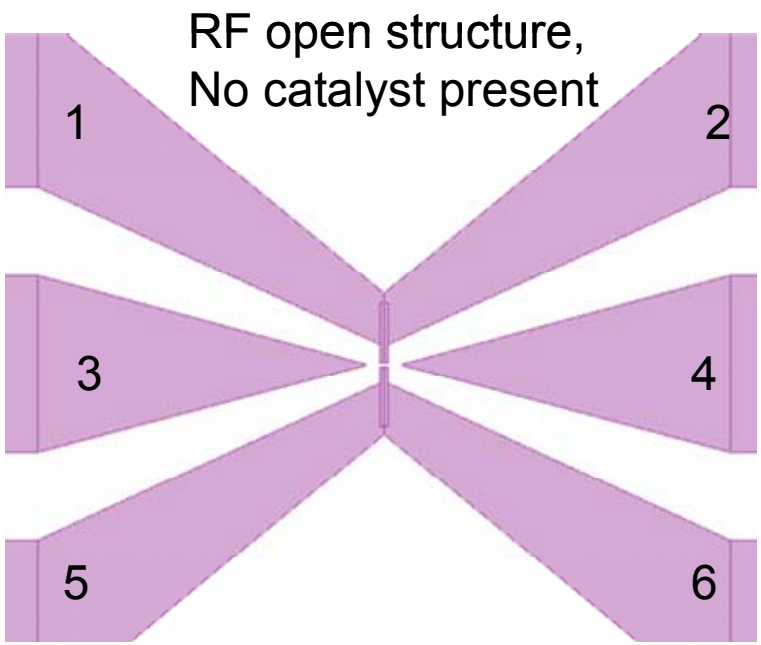
• Thermal CVD was used to mechanically constrain tubes in nanopockets; tubes not self-supporting

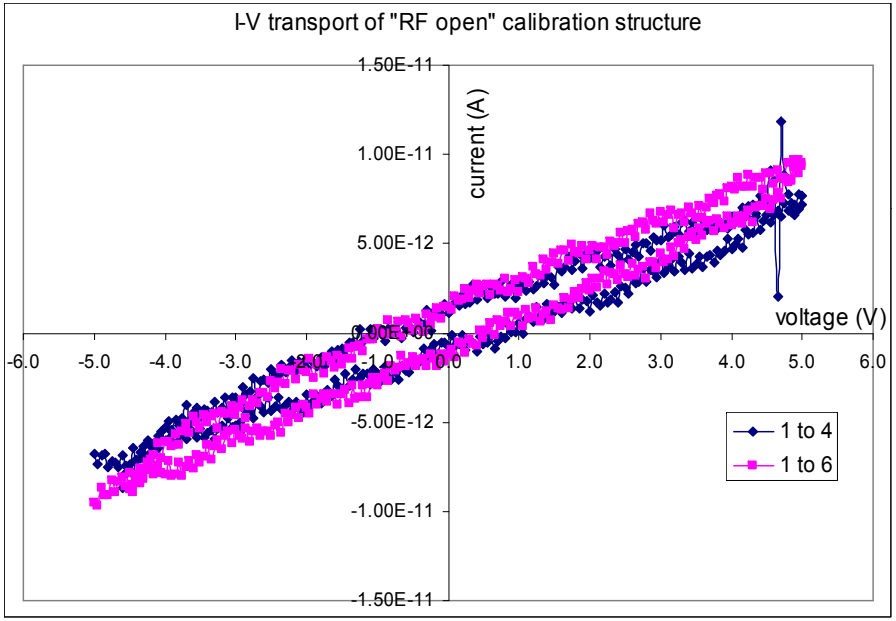
• Demonstrated growth of vertically aligned arrays and single-few MWNTs using dc PECVD with Ni catalyst using optical lithography

• Switch development process is in progress

Backups

Calibration Test Structures





Resistances > 100 GOhms
Leakage currents ~ 10 pA up to +/- 5 V

Device Fabrication Facilities

JPL's Microdevices Laboratory: 12,000 square feet class 10 cleanroom

Contact lithography units

JEOL E-beam aligner
Canon Excimer Laser DUV Stepper

Conventional
RIE etchers (CF_4/BCl_3)

ICP etchers: high density, low pressure plasma (chlorine and fluorine chemistries)

Dektak profilometer

E-beam evaporator (Pt, Ti, Au electrodes)

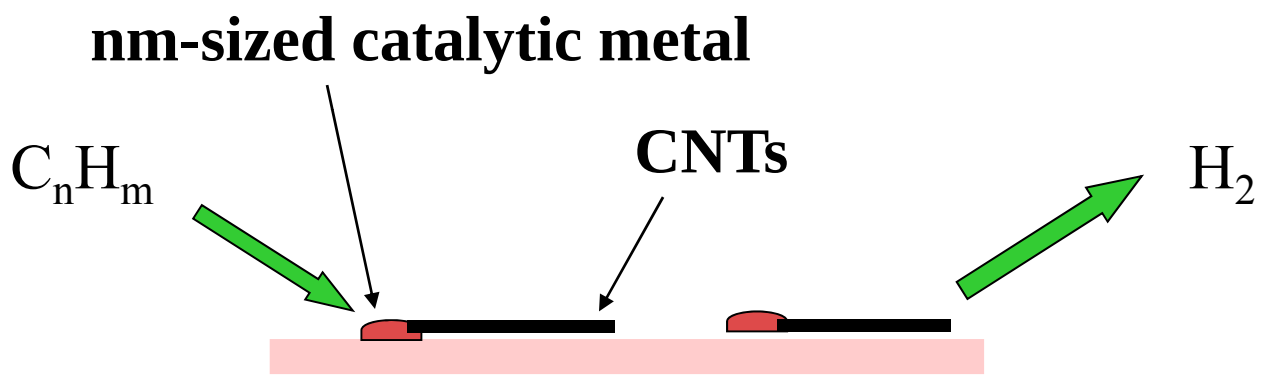
Other key equipment:

- -dc magnetron sputtering system
- -CVD furnace (CNT growth)
- -Fe e-beam evaporator (catalyst layer)
- -PECVD dielectric deposition
- -AFM, SEM (CNT imaging, characterization)

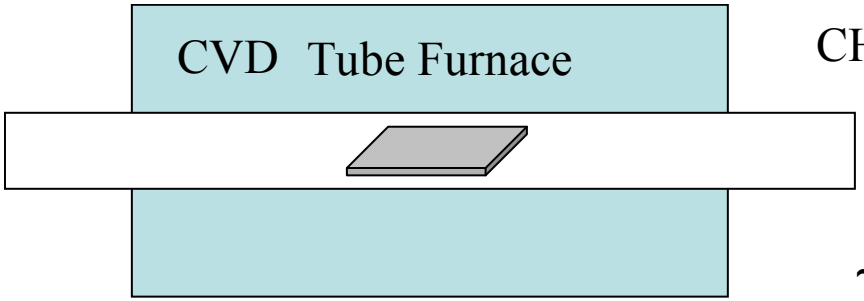
Catalytic CVD Growth of CNTs

High solubility of C in catalyst at high temperatures

Hydrocarbons (C_nH_m) $\xrightarrow[\text{600-800 C}]{\text{Fe (or Ni, Co, etc.)}}$ **C(s) + H_2**



SWNT Synthesis Conditions



CH_4 1500 sccm & H_2 50 sccm @ 850 ºC

2” Quartz Tube

~ 1 nm thick Fe-catalyst film

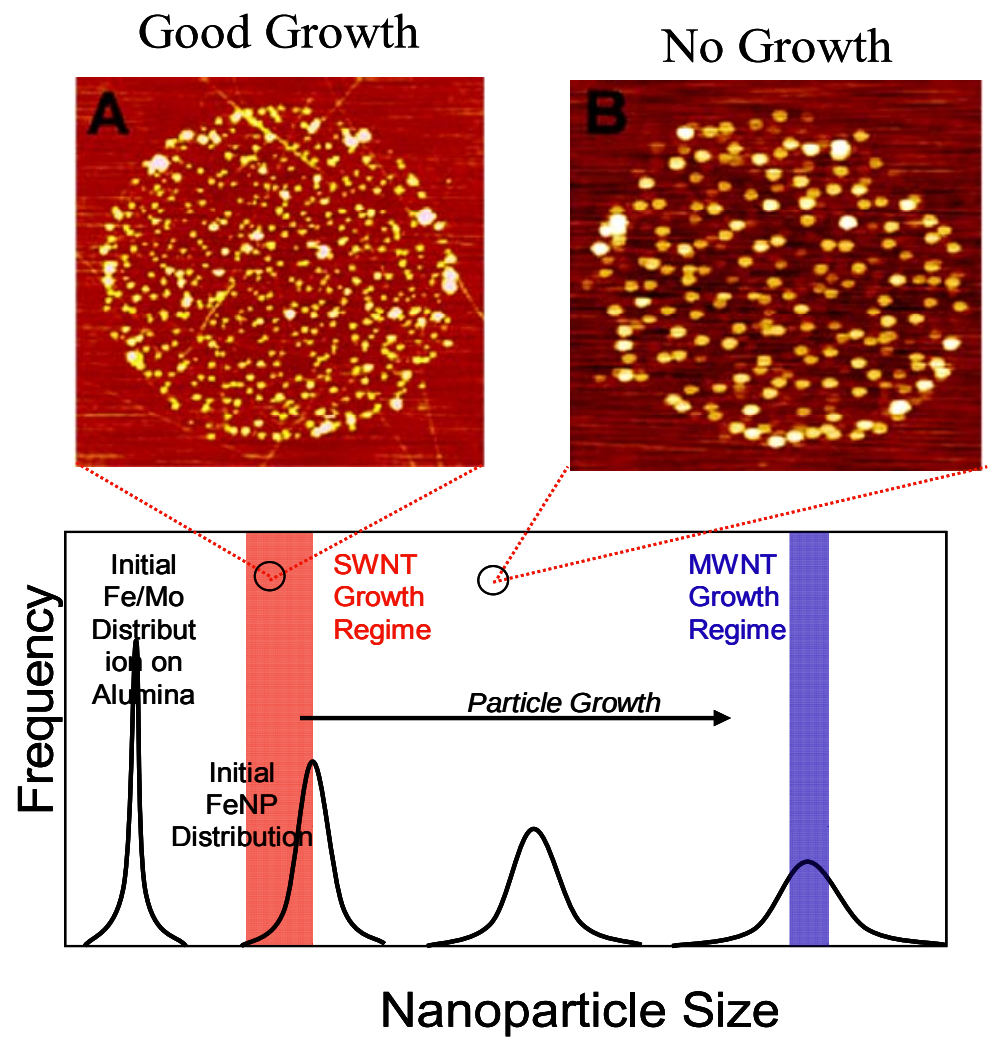
CVD Synthesis of SWNTs

Role of H_2

- H_2 required to minimize amorphous carbon, but too much H_2 or hot annealing causes particle fusion and inhibition of SWNT growth
- Particle growth desirable for larger MWNTs

Gas flow dynamics

- Stagnant zone in boats results in variable gas mixing leading to variable SWNT yield
- Flat top holders with laminar flow give consistent results



Wong, E.W. *et al.*, *Chem. Mater.*, **17** (2005) 237-241