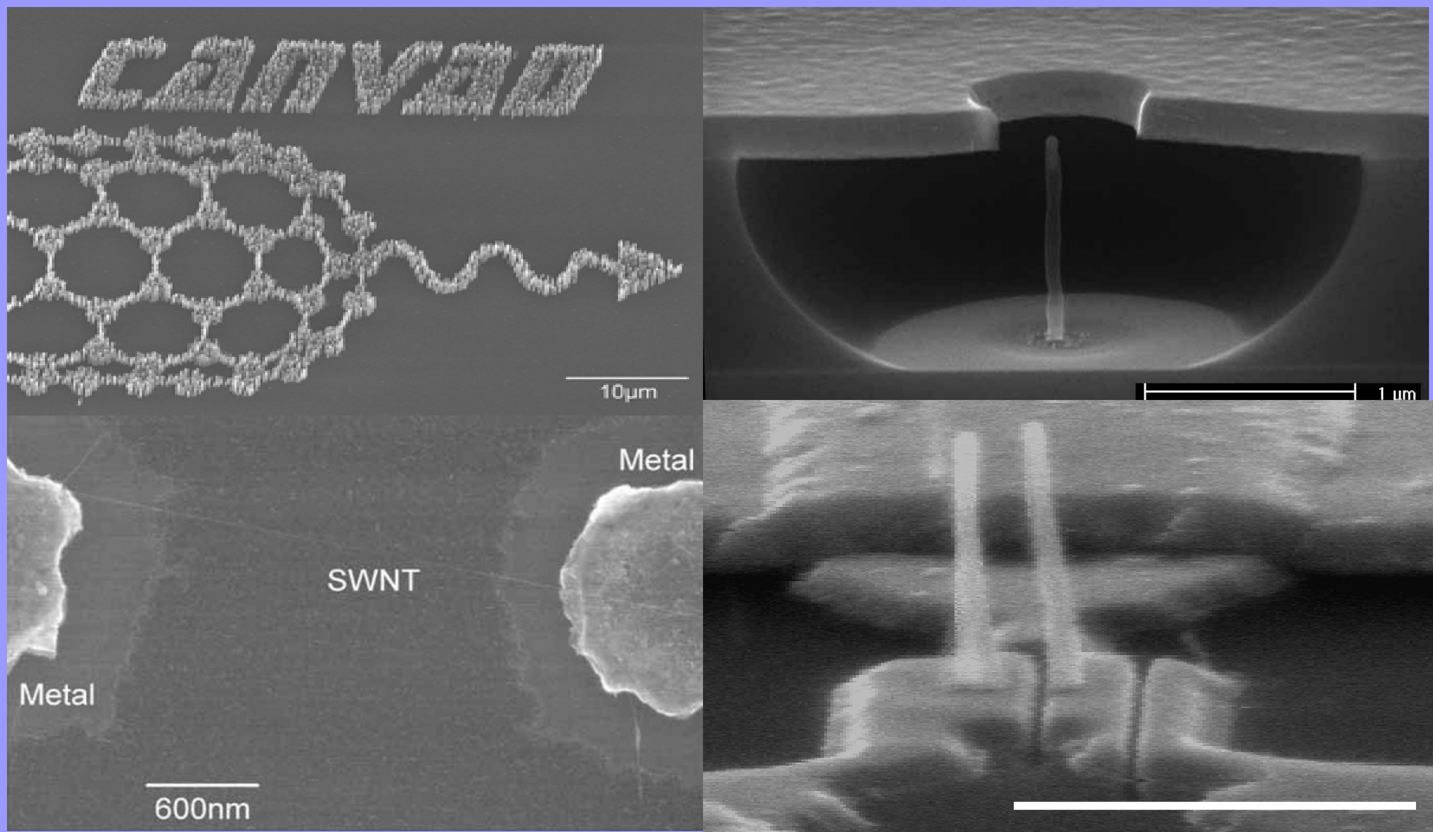
Carbon Nanotubes for Electronic Applications?



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Samsung
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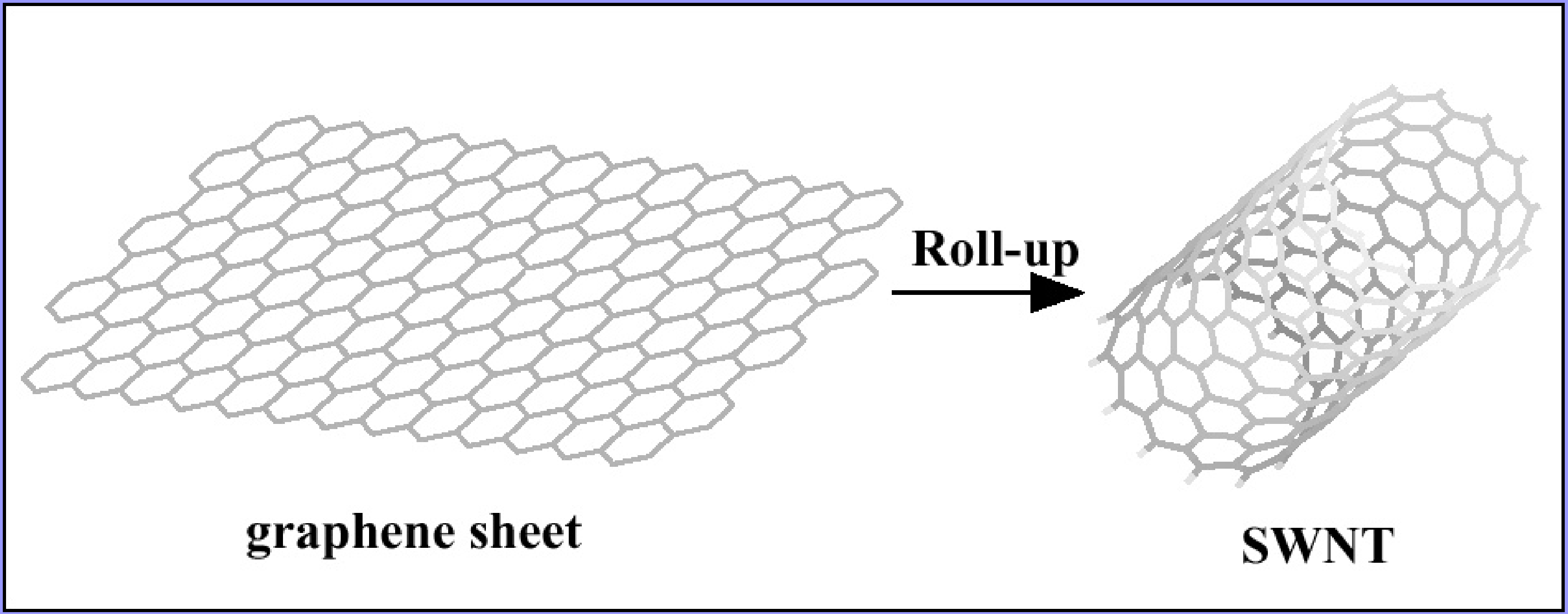
PROMENADE,CANVAD, NANOLITH, DESYGN-IT, CARDECOM,CANAPE, NANORAC, CANDICE etc

- Introduction
- Growth of Carbon Nanotubes
- Optimisation of CNTs
- Near Term Applications
- Longer Term
- Conclusions

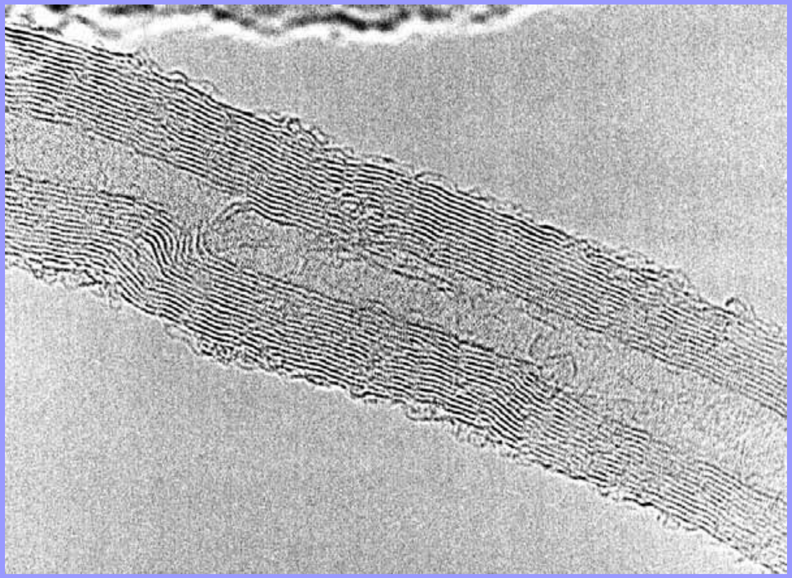
What are CARBON Nanotubes

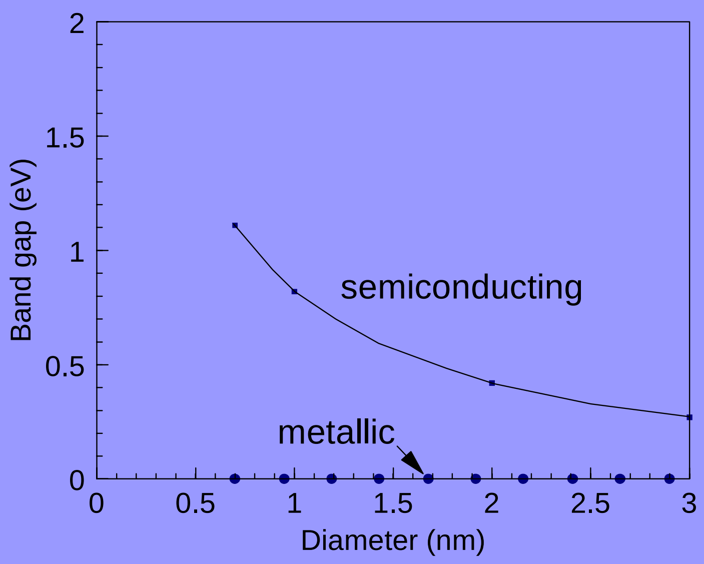
- Single wall nanotubes can be semiconducting!

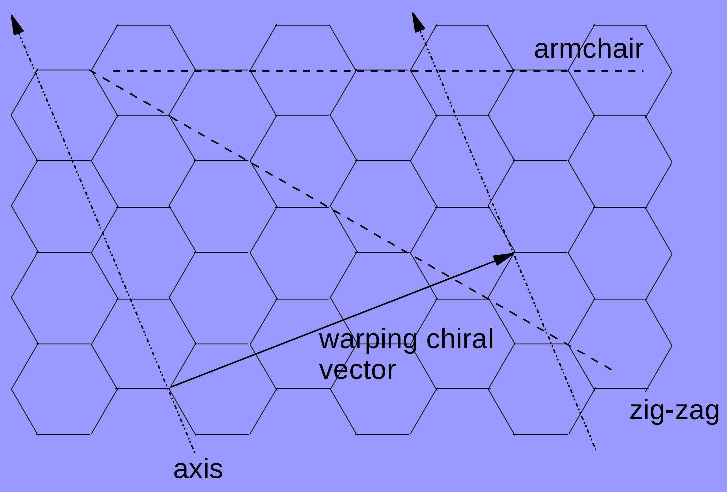


- It all depends on the angle of rolling and diameter of the nanotube.

- Rolled up graphite sheets
- no unsatisfied surface bonds
- Single walled or multi-walled
- Metallic or semiconducting
- Band gap of SWNTs = f(chirality, diameter) or 'wrapping vector' (n,m)
- Multi-walled are metallic







Uniqueness of CNTs

Unique properties of

- Sharp - aspect ratio – field emission, electrical composites
- Highest current density 10^9 A/cm^2 – Vias, FE,
- Ballistic electron transport - FETs
- Highest Youngs modulus, ~1TPa - composites
- Highest thermal conductivity, 4000 W/m.K - composites
- Electrode potential range/surface area – sensors, supercaps

Growth of Carbon Nanotubes

- Electric arc discharge between graphite electrodes
- Laser ablation
- Catalytic chemical vapour deposition (CVD)

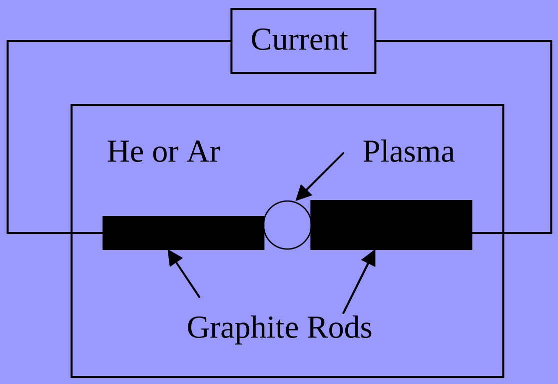
Synthesis Techniques

1. Arc-discharge Method

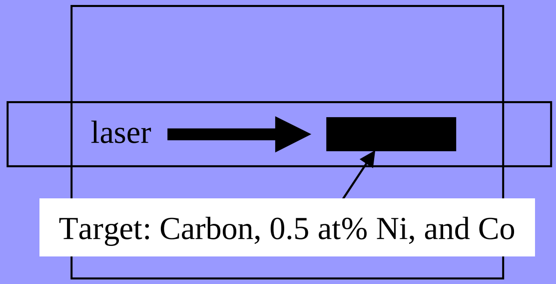
- Producing MWNT & SWNT
- Two graphite rods are used as electrodes and He or Ar gas used for inert atmosphere condition during arc-discharge

2. Laser Ablation Method

- Producing SWNT
- Intense laser pulses are utilized to ablate a carbon target containing 0.5at % of nickel and cobalt.



(a) arc-discharge



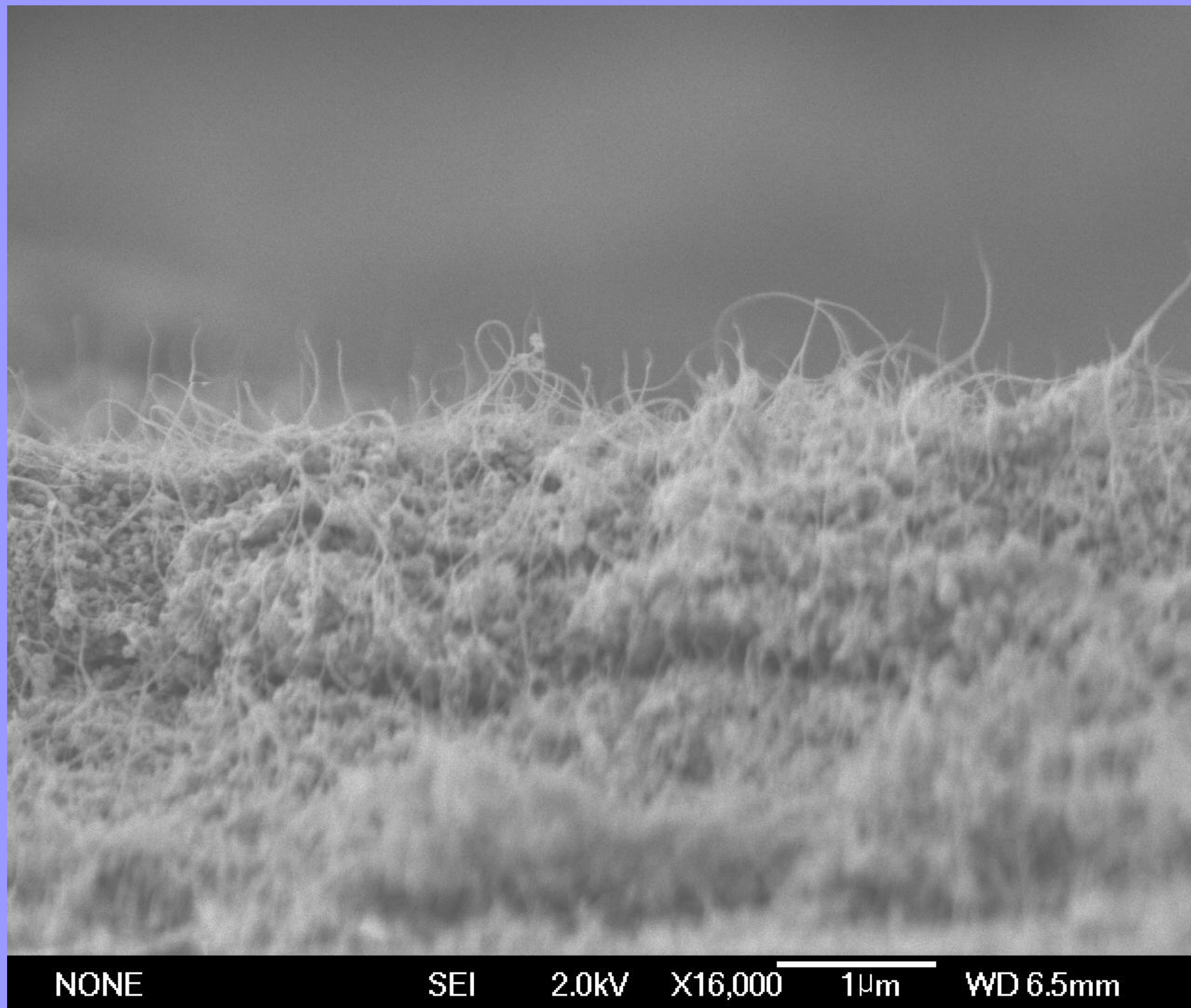
(b) laser ablation

*** Advantage** -Production of high quality carbon nanotubes

*** Disadvantages** -High temperature process

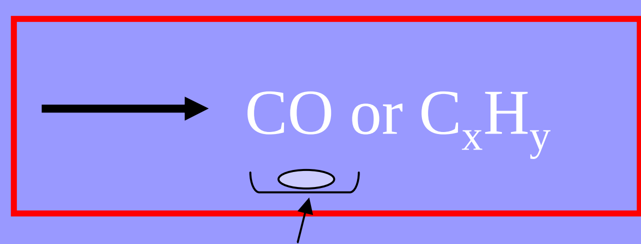
-Grow carbon nanotubes in highly tangled forms with unwanted carbon and metal impurities.- need to purify

-Hard to control

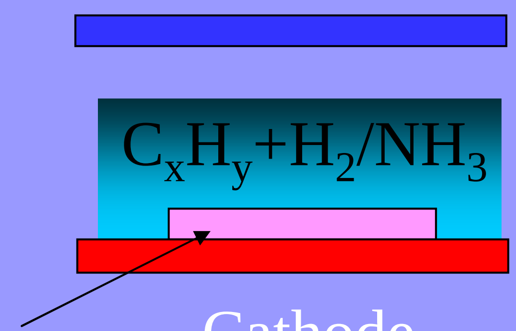

NONE
SEI
2.0kV
X16,000
1μm
WD 6.5mm

Catalytic Chemical Vapour Deposition

Thermal CVD



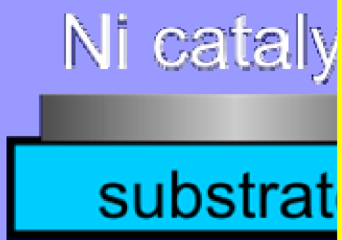
Plasma CVD



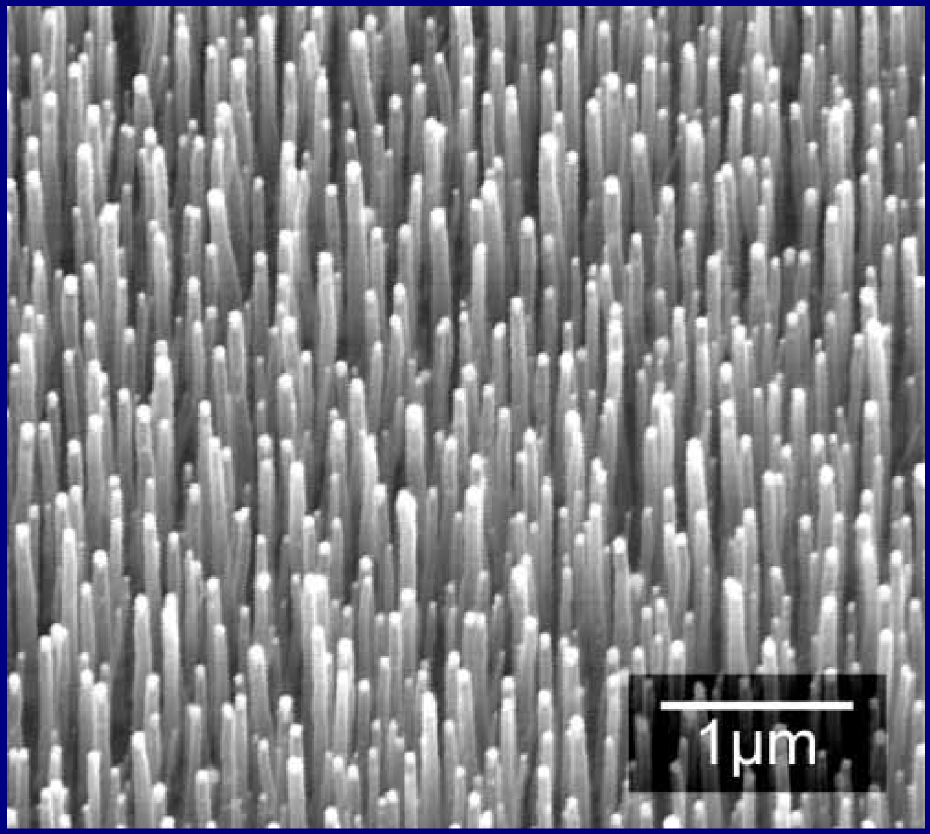
Advantages: no purification needed, direct on substrate growth vertical floating technique can run continuously

Disadvantages: expensive compared with arc

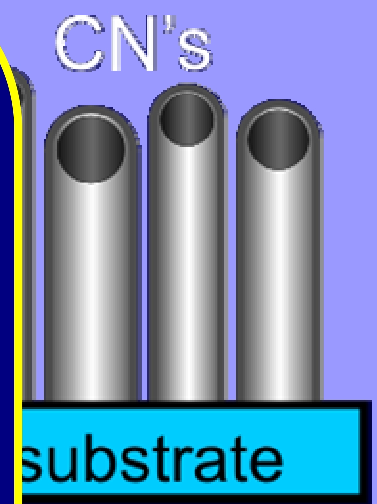
Growth Process of CNTs



CNTs grown from Ni clusters



Bright dot at CNT top = catalyst cluster



- Step 1: At
agglomera
- Step 2: PE … CNTs,
NH_3 is the c

CNTs by Plasma Enhanced CVD

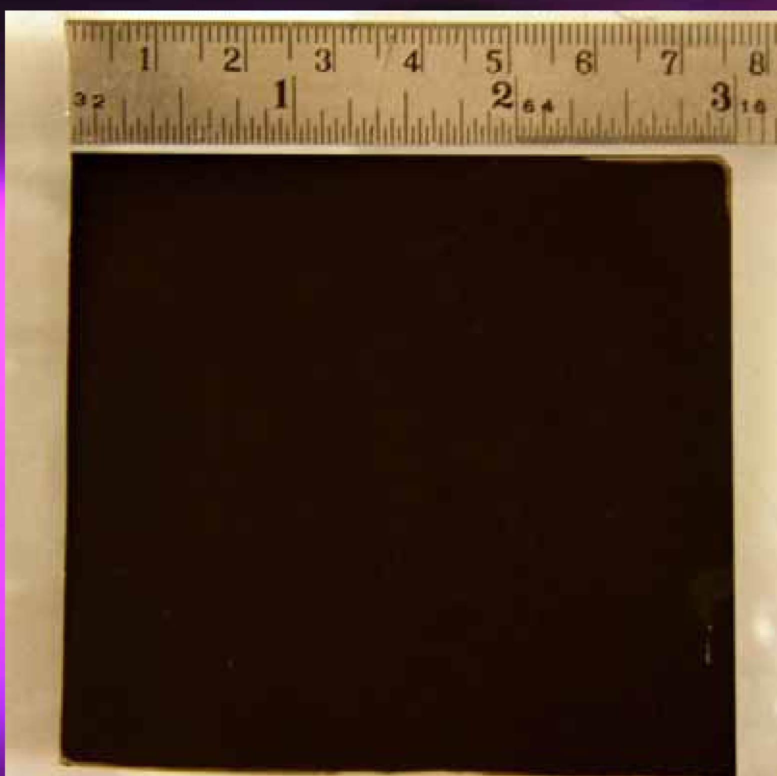
Anode

- Aligned growth
- High yield
- Uniform
- Diameter/length control
- Selective growth
- Can be large area

PECVD references

HF+DC: Ren, Science **282**, 1105 (1998)
DC: Merkulov, APL **76**, 3555 (2000)
Microwave: Bower, APL **77**, 830 (2000)
DC: Chhowalla, JAP **90**, 5308 (2001)
ICP: Delzeit, JAP **91**, 6027 (2002)

Thermo couple



Plasma

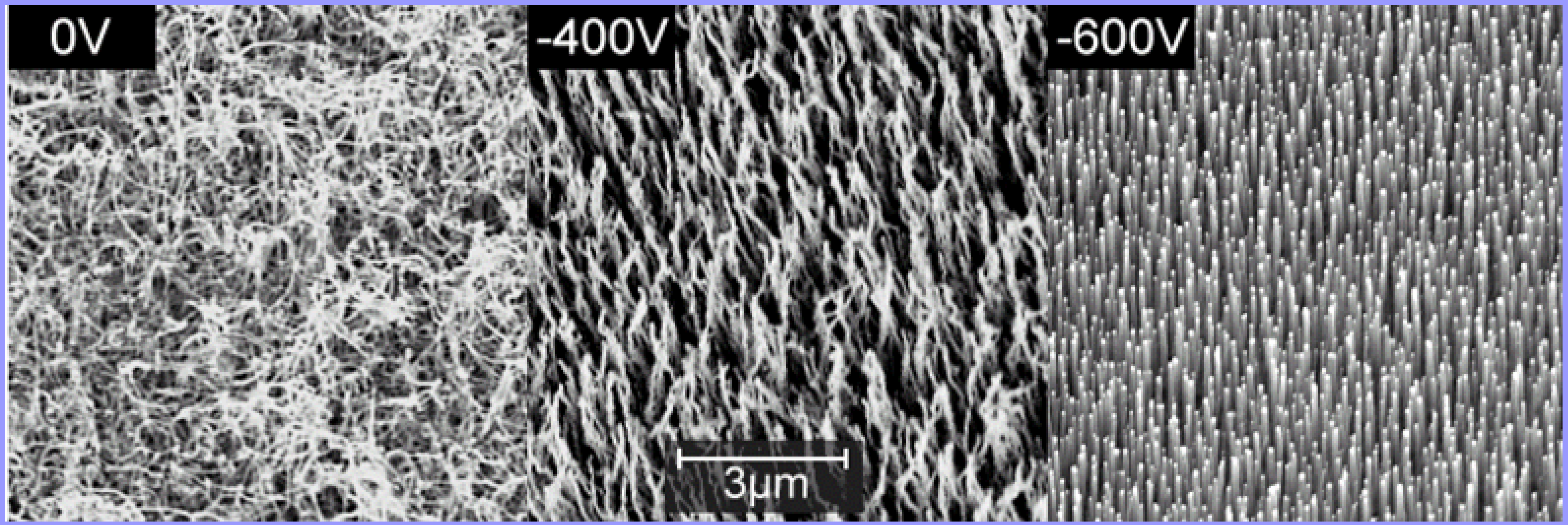
substrate

Heated cathode

Deposition equipment
Is available from
Cambridsge Nanoinstruments

We use a PECVD Method of Growth for Multiwall CNTs-

Influence of Plasma Voltage on the Alignment of Nanotubes



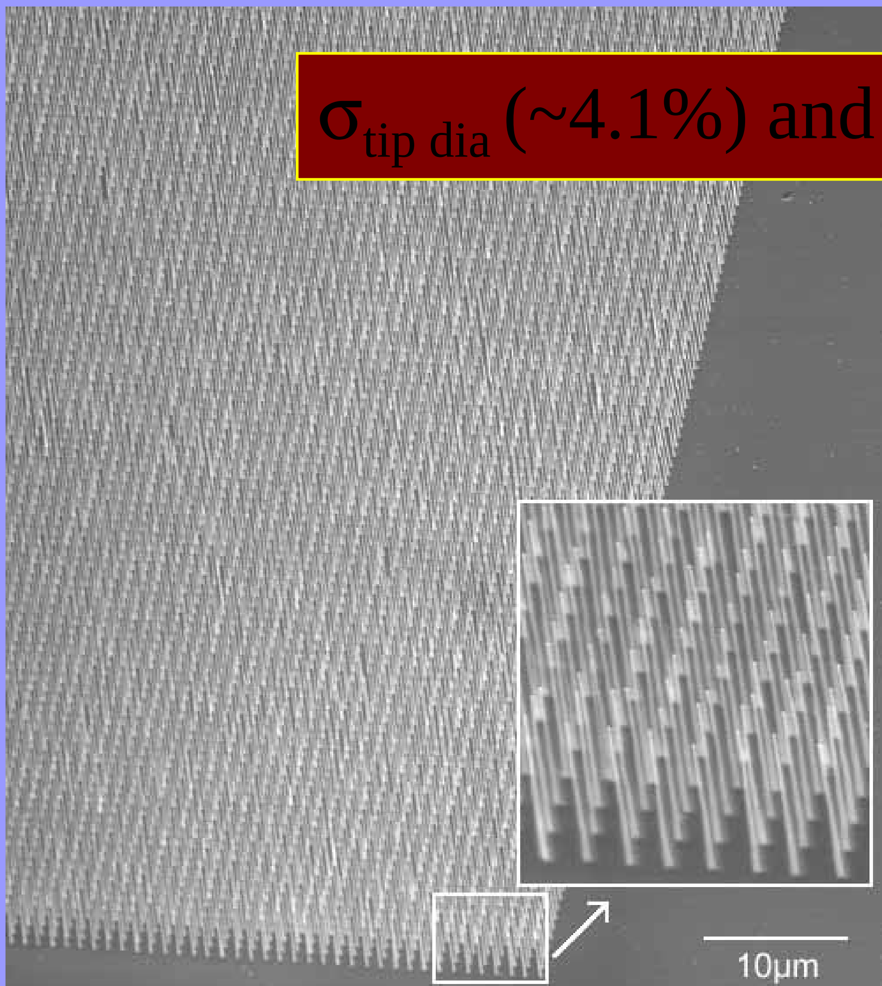
E = 0 V/μm

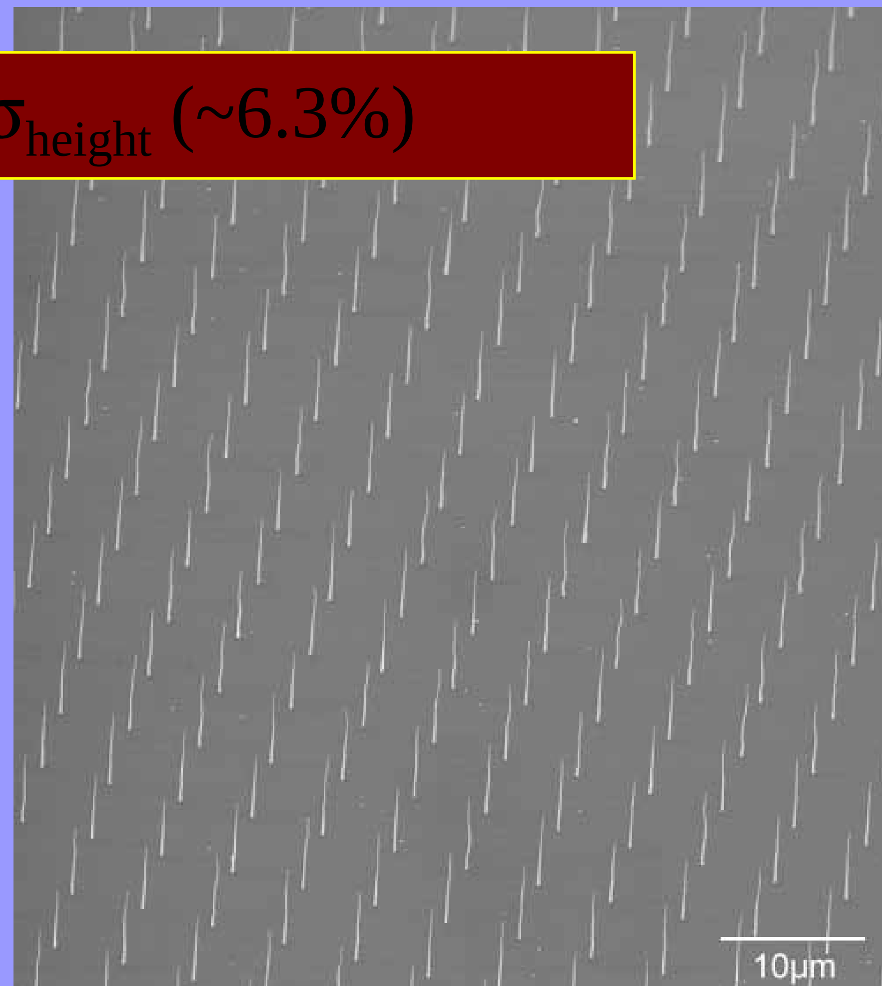
E = 0.1 V/μm

E = 0.35 V/μm

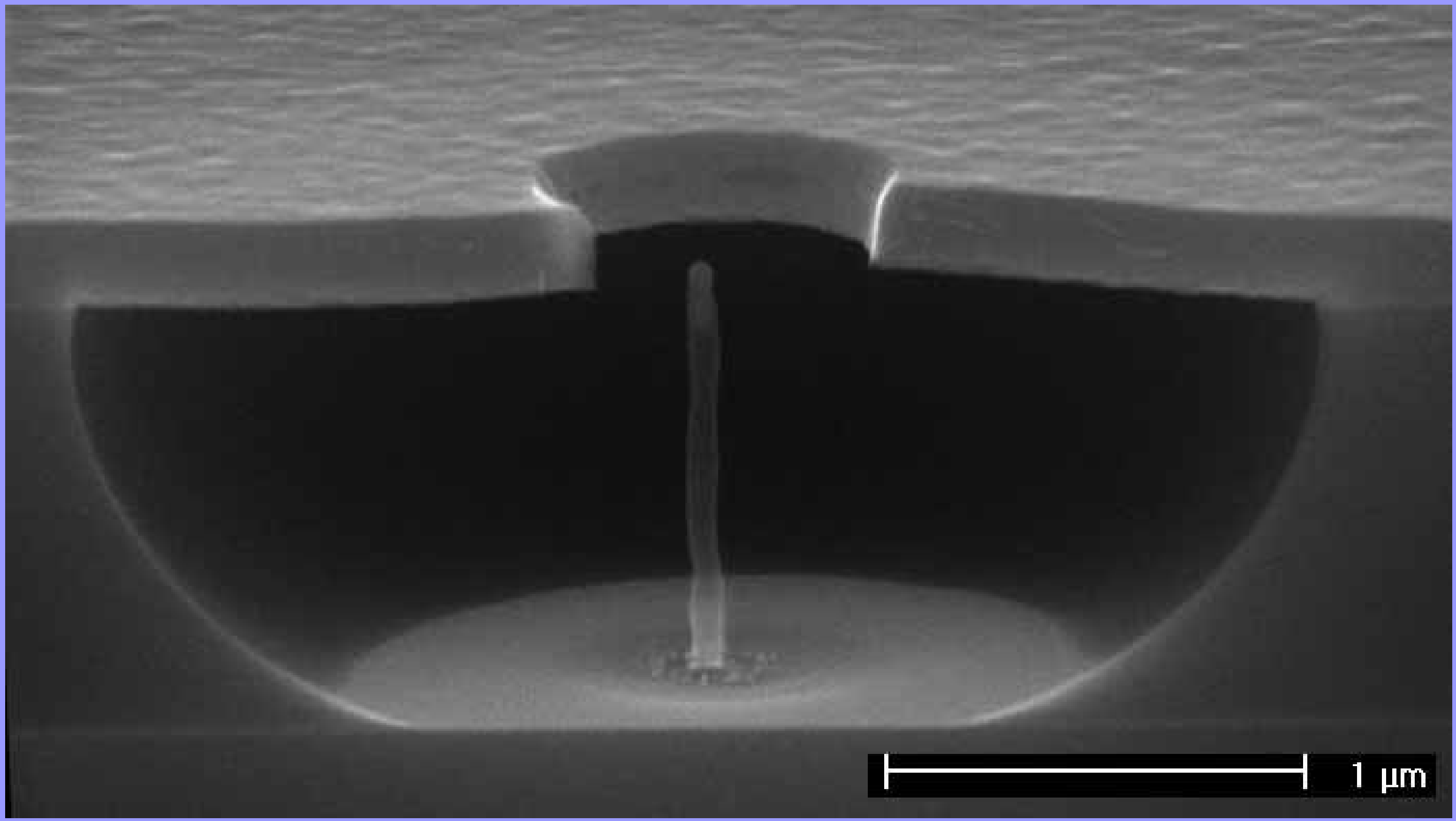
Designable CNT Arrays

$\sigma_{tip\ dia}$ (~4.1%) and σ_{height} (~6.3%)

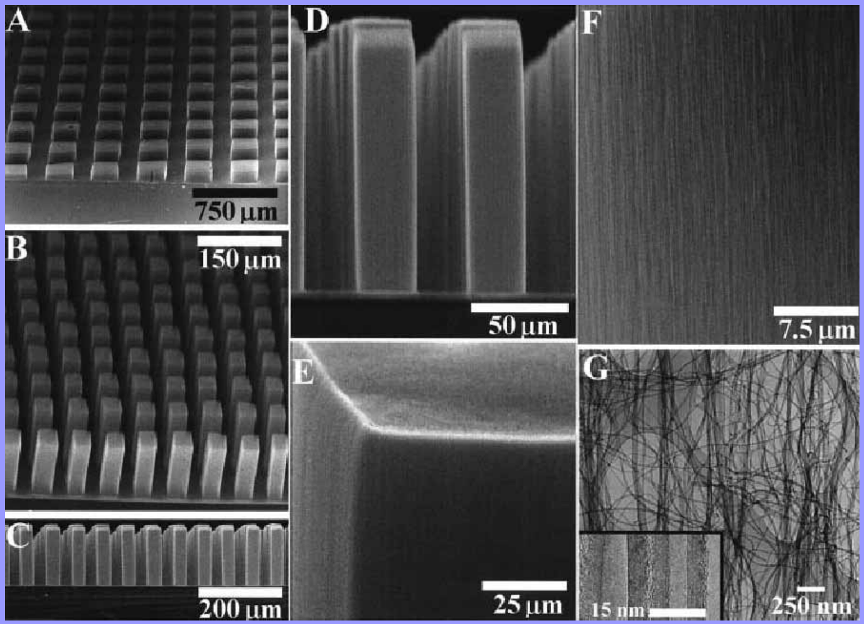




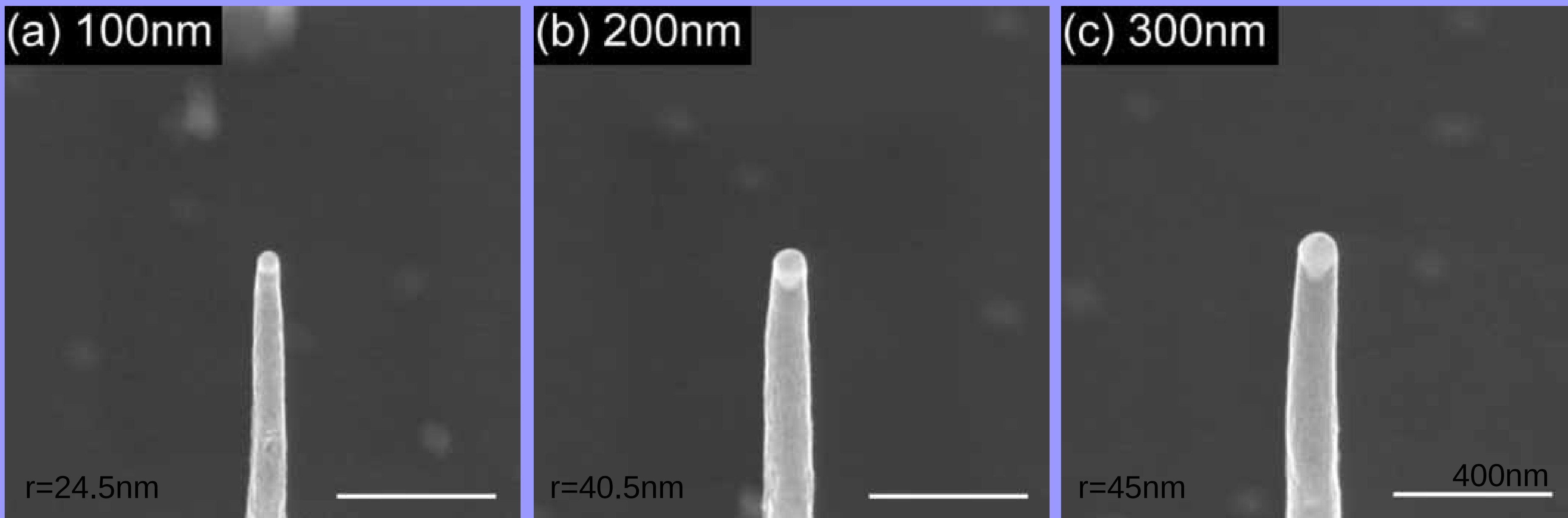
160nm litho, 10μm pitch, 5μm tall CNTs (45mins growth)


1 μm

Fan et al, Science **283**, 512 (1999)



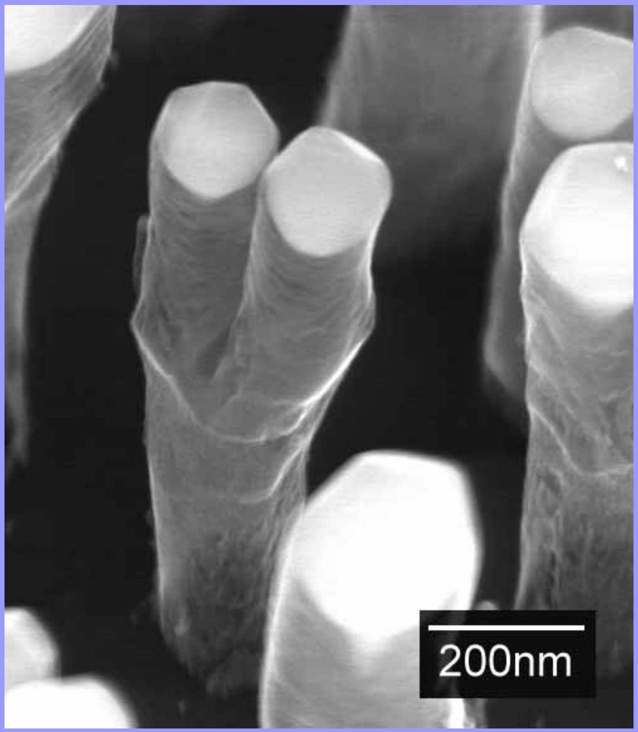
Regular tip shape



Different diameter CNT from different catalyst dot sizes

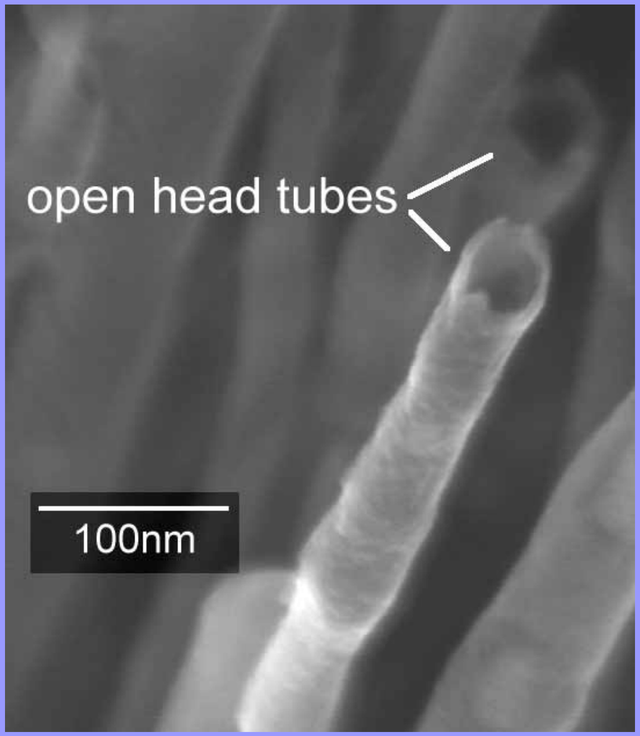
Hemispherical cap gives the whisker shape which agrees with beta=h/r theory

Other interesting PECVD structures



Branched

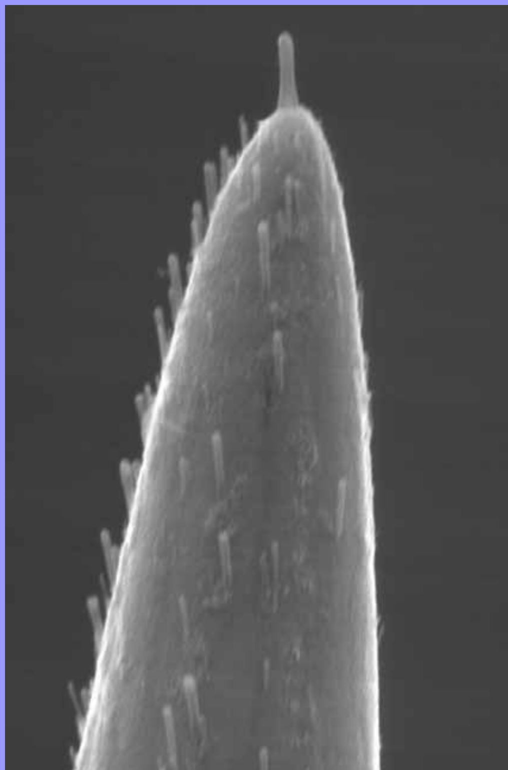
Coated



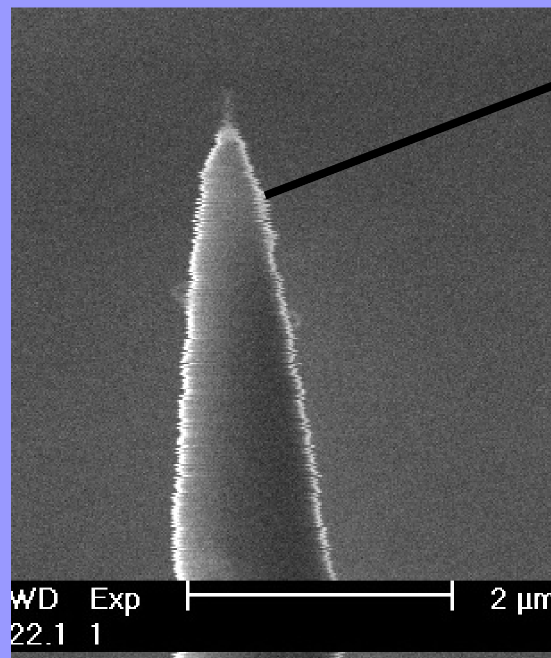
Open

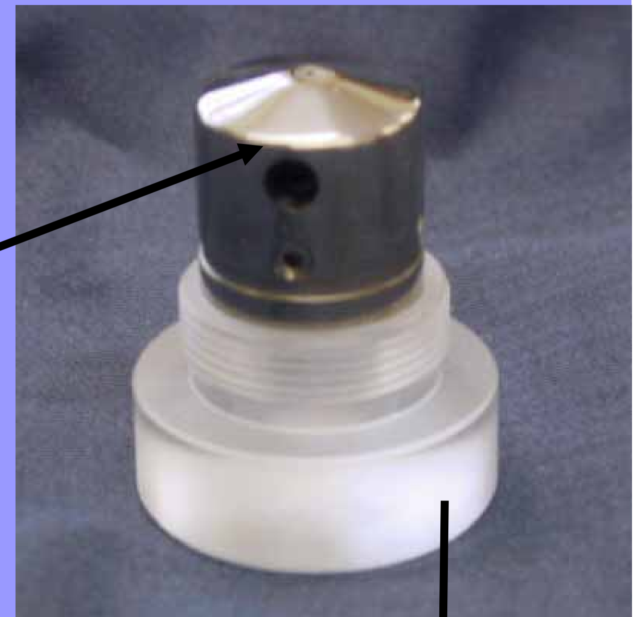
Near term applications

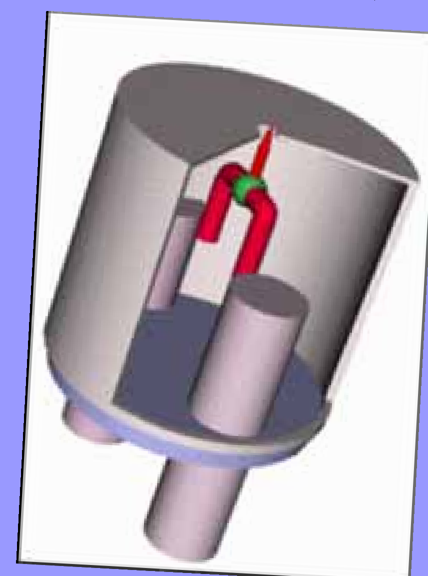
- Field emission



In collaboration with
FEI and York Univ.







Electron Microscopes

e- Guns for SEM

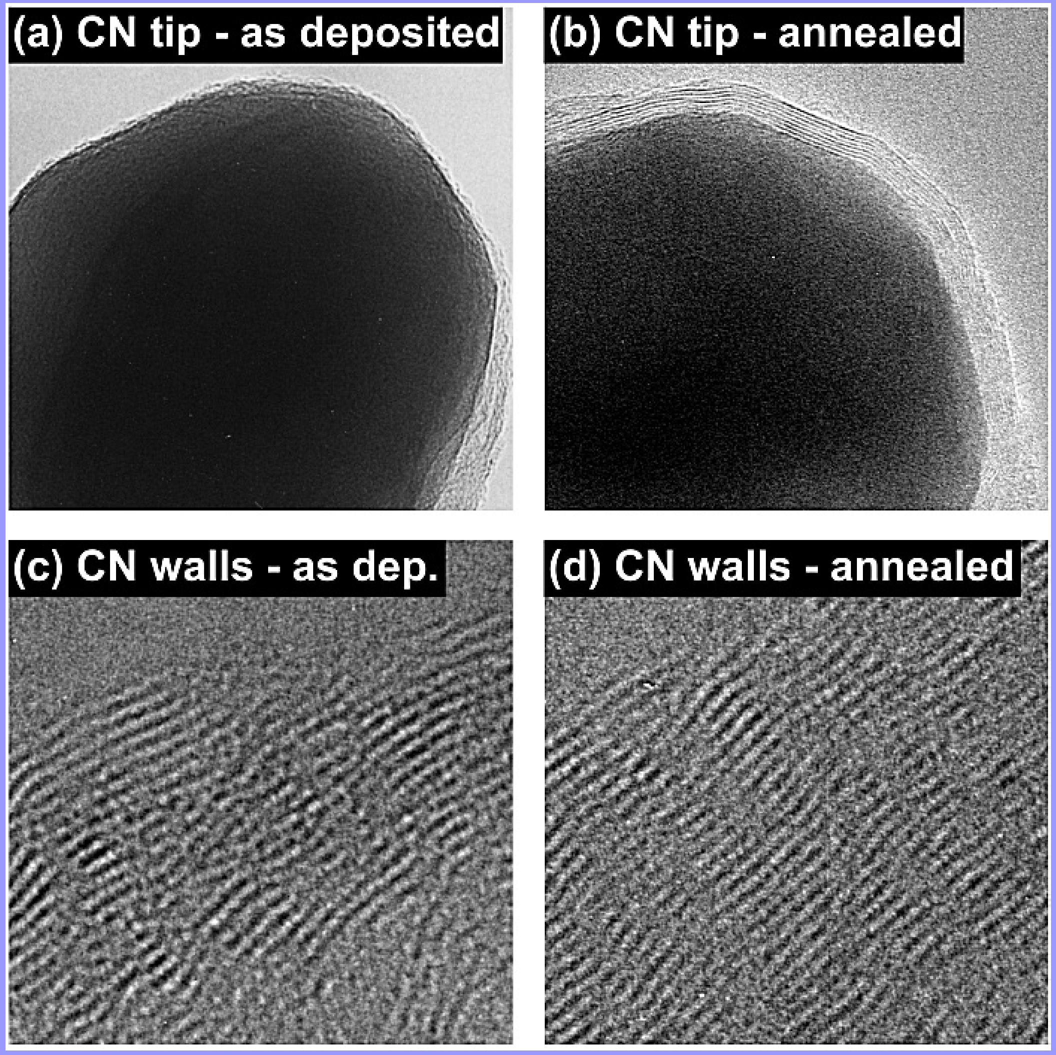
- Replace Si ‘Schottky’ emitters
- Use MWNTs due to greater stiffness

- High max current density
- Small source size – 2nm
- Narrow Energy Width – 0.25 eV
- High brightness = 3.10^{9} A/(m^{2}Sr.V)
- N deJonge et al (FEI/Philips), Nature 420 393 (2002); JAP 95, 673 (2004)

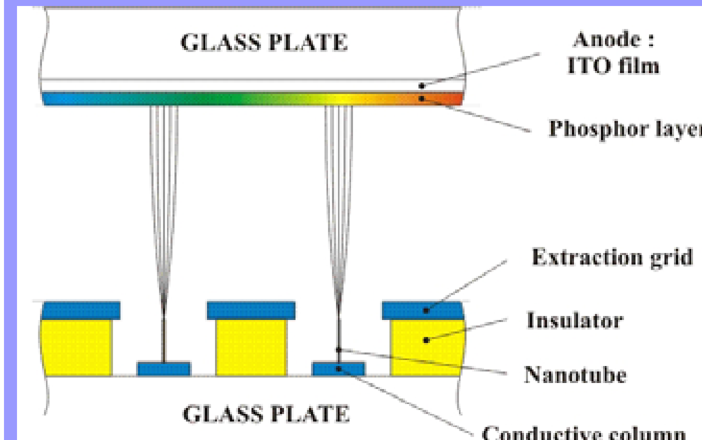
	Cold FE	Schottky	CNT
ΔE (eV)	0.25	0.7	0.25
r (nm)			2
B (A/Sr/m^{2}/V)	10^{7}	10^{8}	$3x10^{9}$

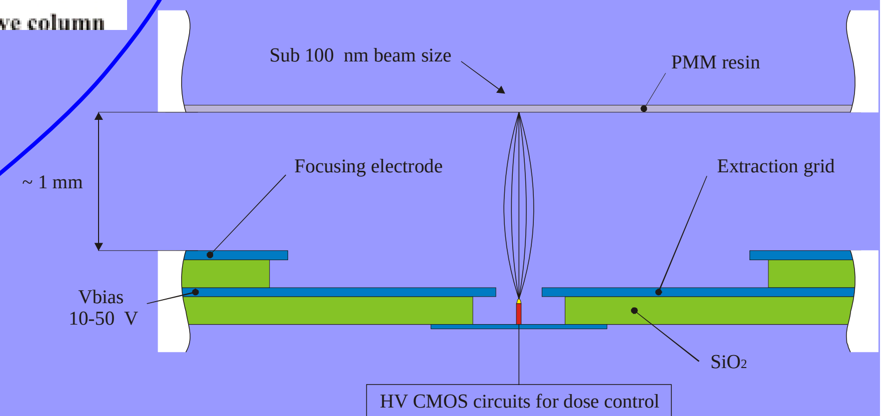
- Manufacturability
- Current stability

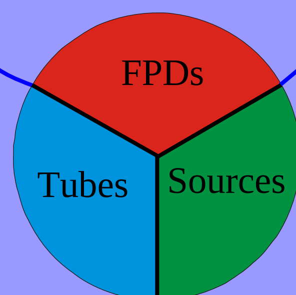
Towards high quality emitters

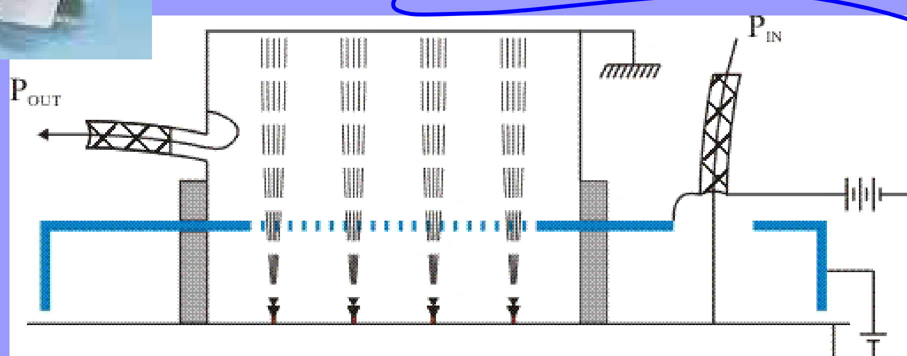


Other Field Emission Applications





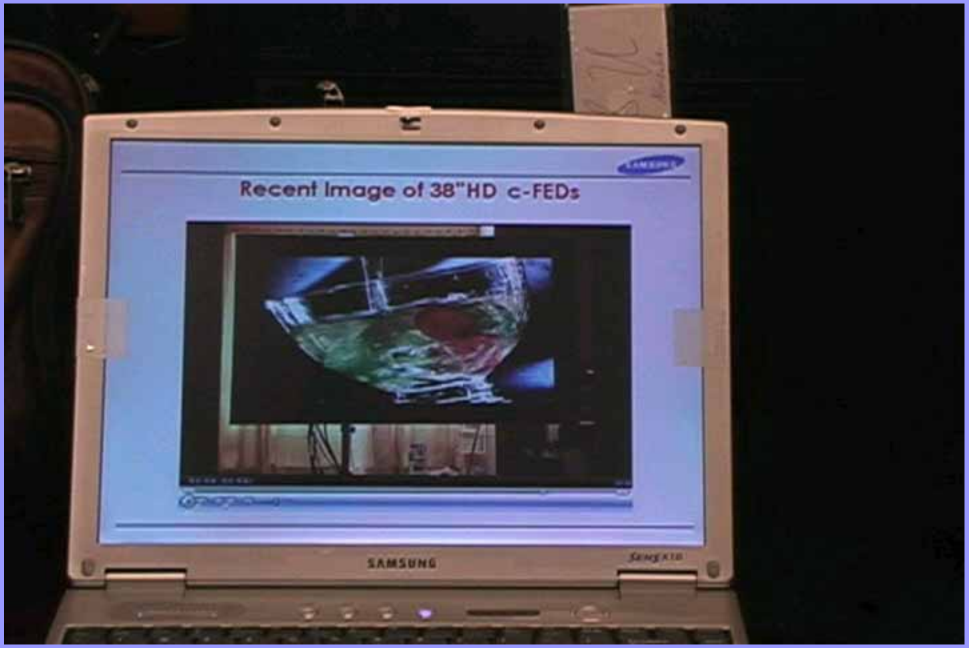




SAMSUNG 38” Multi Colour CNT based FED

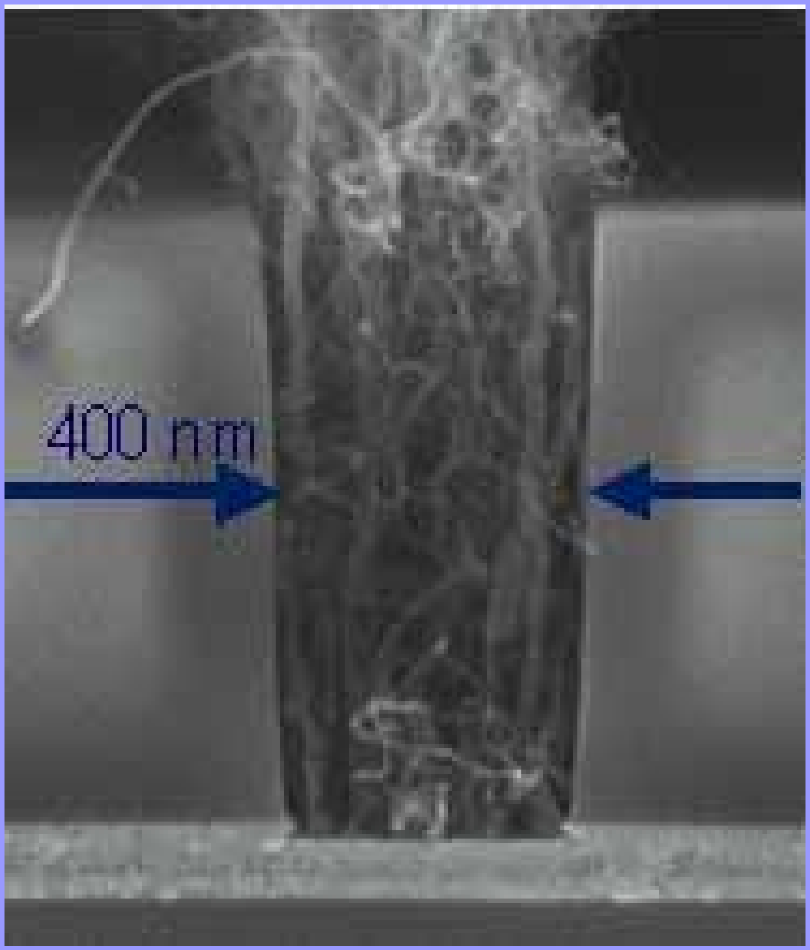
- **Shows significant improvemenent since first shown in 2002**
- **Dr.J. M. Kim SAIT(IVMC 2003)**

No line defects and Very few point defects



Longer Term Applications

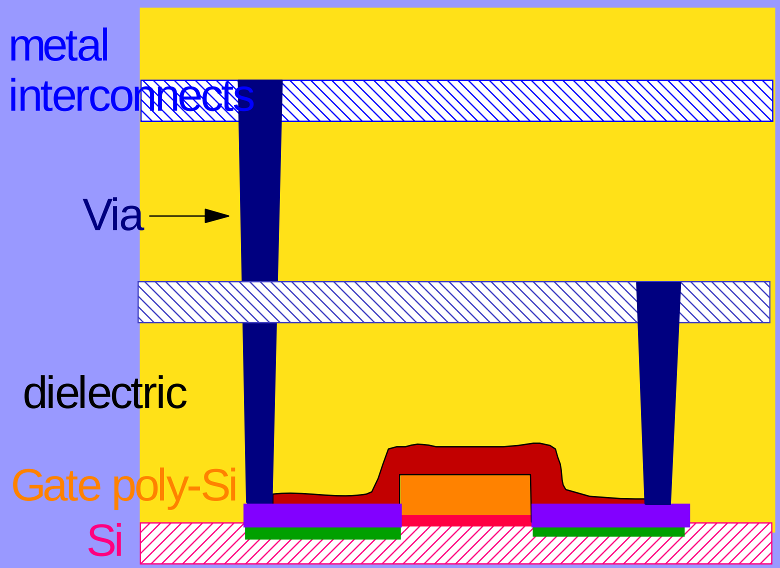
Vias/Interconnects
Transparent Conductors
MEMS/NEMS
Bio/Gas/ Chemical Sensors
Transistors/logic
Solar Cells
Energy Storage Devices
etc



Multiwalled nanotubes grown by catalyst mediated selective CVD in a via

from INFINEON WEBPAGE

Electronics –Interconnects in ICs



Cross-section of an Integrated Circuit

- Electromigration limits max current density in IC interconnects
- $J = 10^5$ A/cm^2 (Al), 10^6 A/cm^2 (Cu)
- CNTs have strong covalent bonds – less electromigration

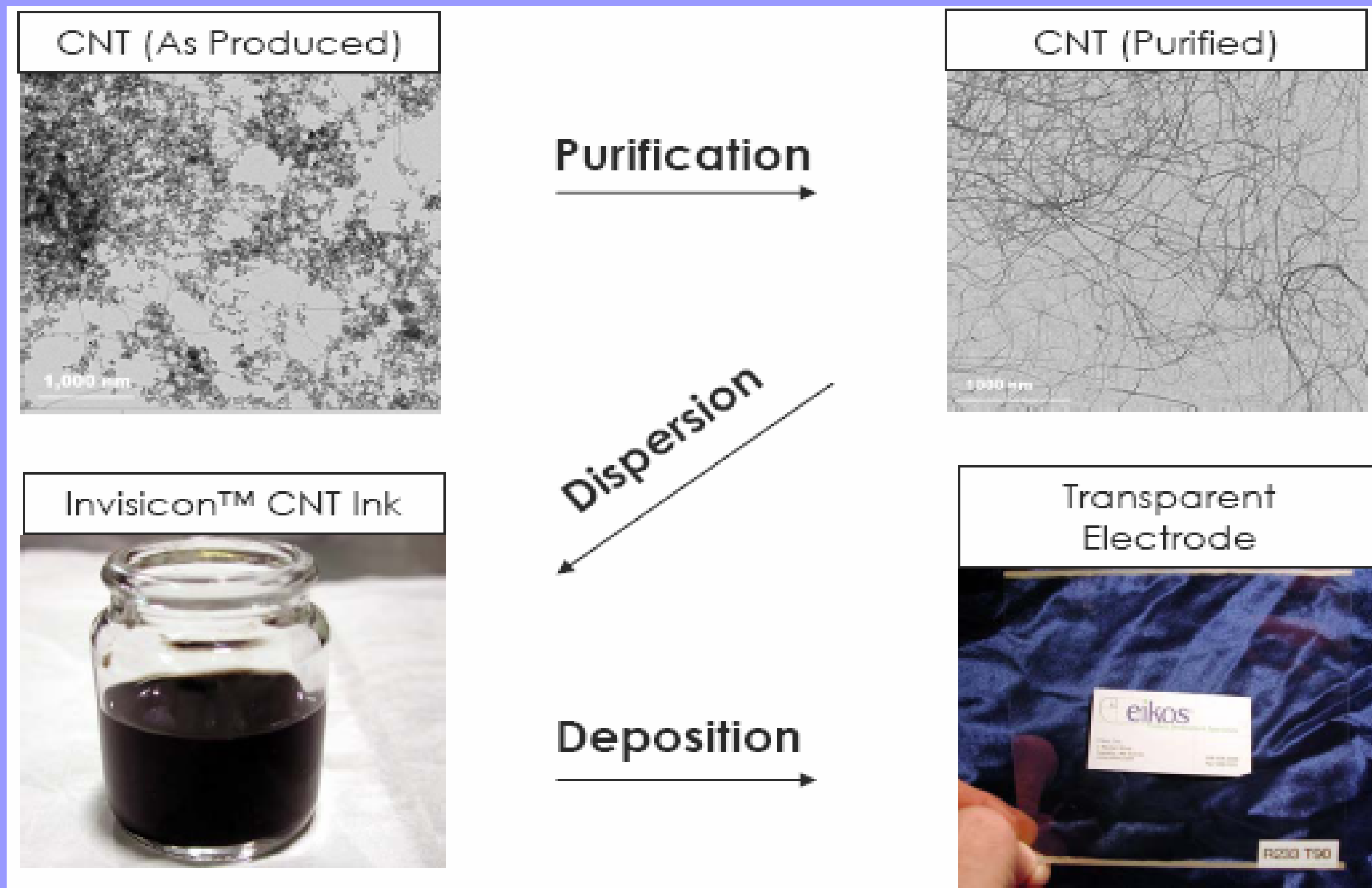
  $J_{max} = 10^9$ A/cm^2

- Vias - vertical growth ideal for PECVD e.g.(Infineon) A P Graham, IWEP 2003
- Uses metallic MWNTs

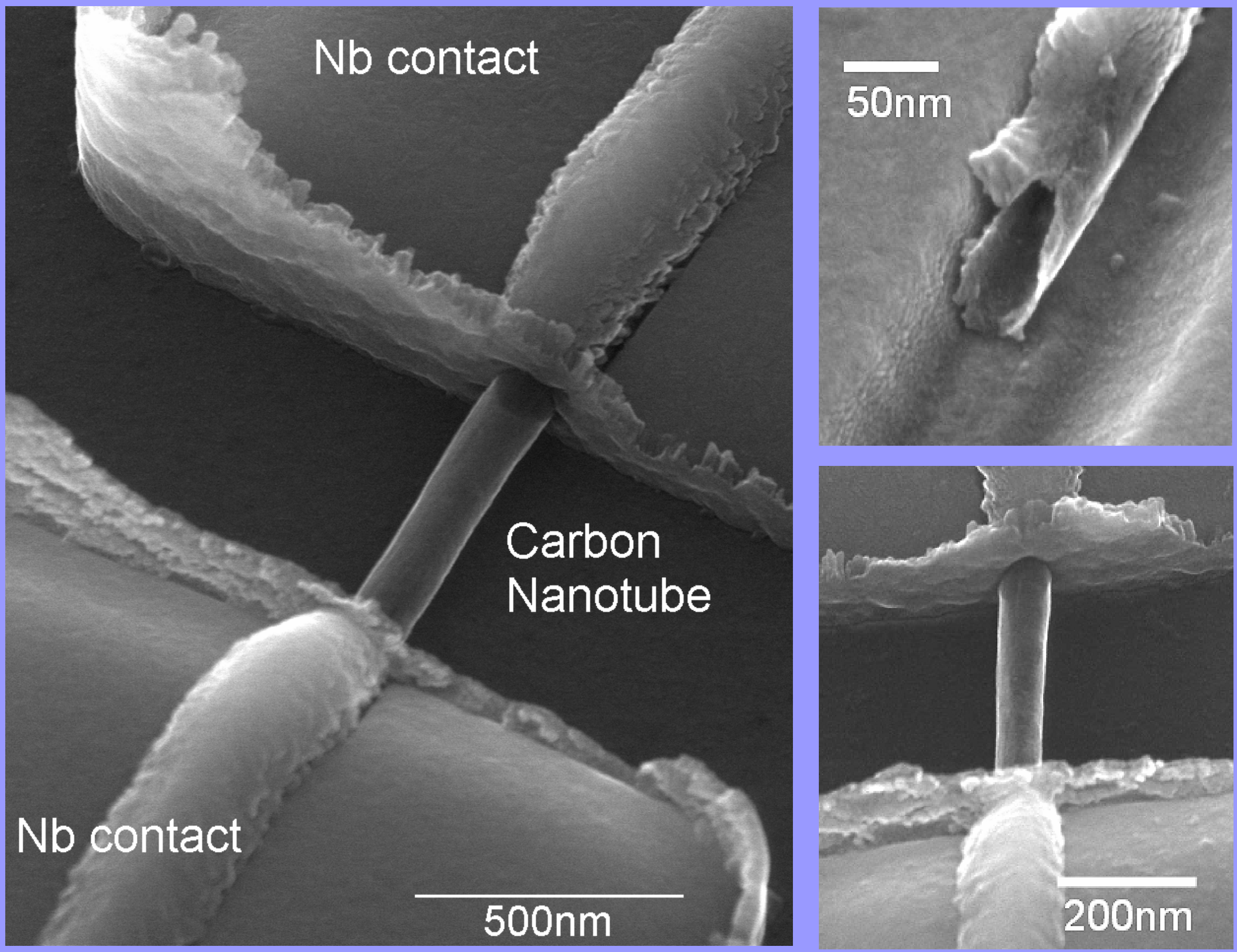
Problems to overcome

- Back-end processes – so need to limit growth to ~450 C not 600C
- So major need to improve quality of 450C PECVD MWNT
- For 2 micron via CNTs resistance is about 5 Ω - currently about two orders higher than Cu and 1 order higher than W
- Contacts to interconnects/packing density/ diameter of tubes
- Currently 10^{10}cm^{-2} - aiming for 10^{12} cm^{-2}

Possible ITO replacement for Flexible Displays (Eikos)

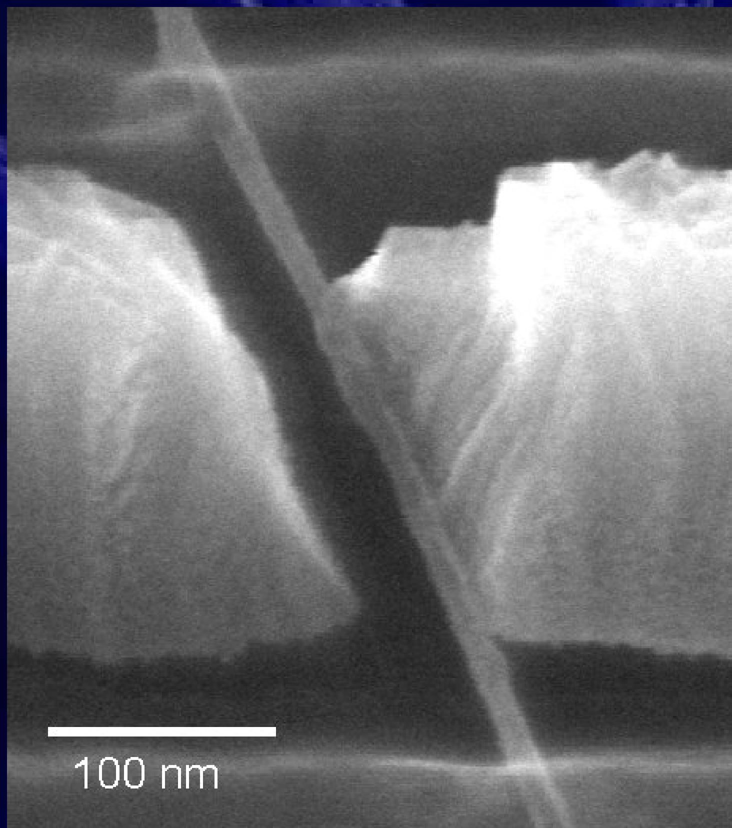


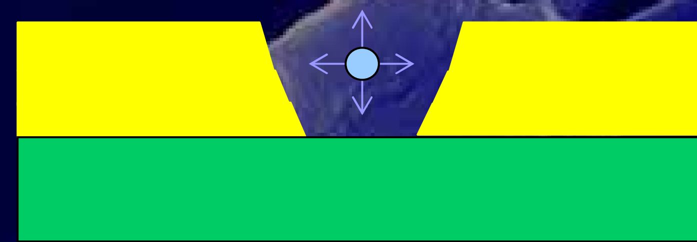
MEMS/NEMS



Nb contact
Carbon
Nanotube
Nb contact
500nm
50nm
200nm

Possible application - Oscillator





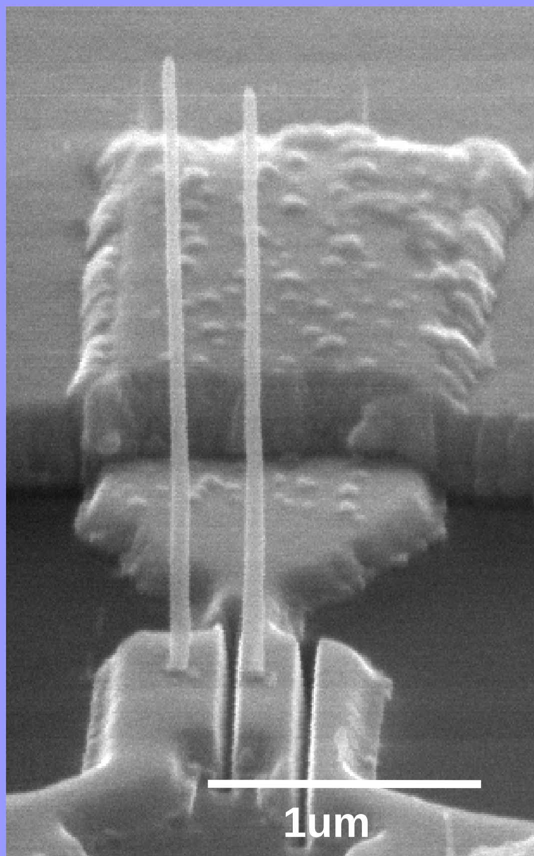
- Nano-electromechanical Oscillator

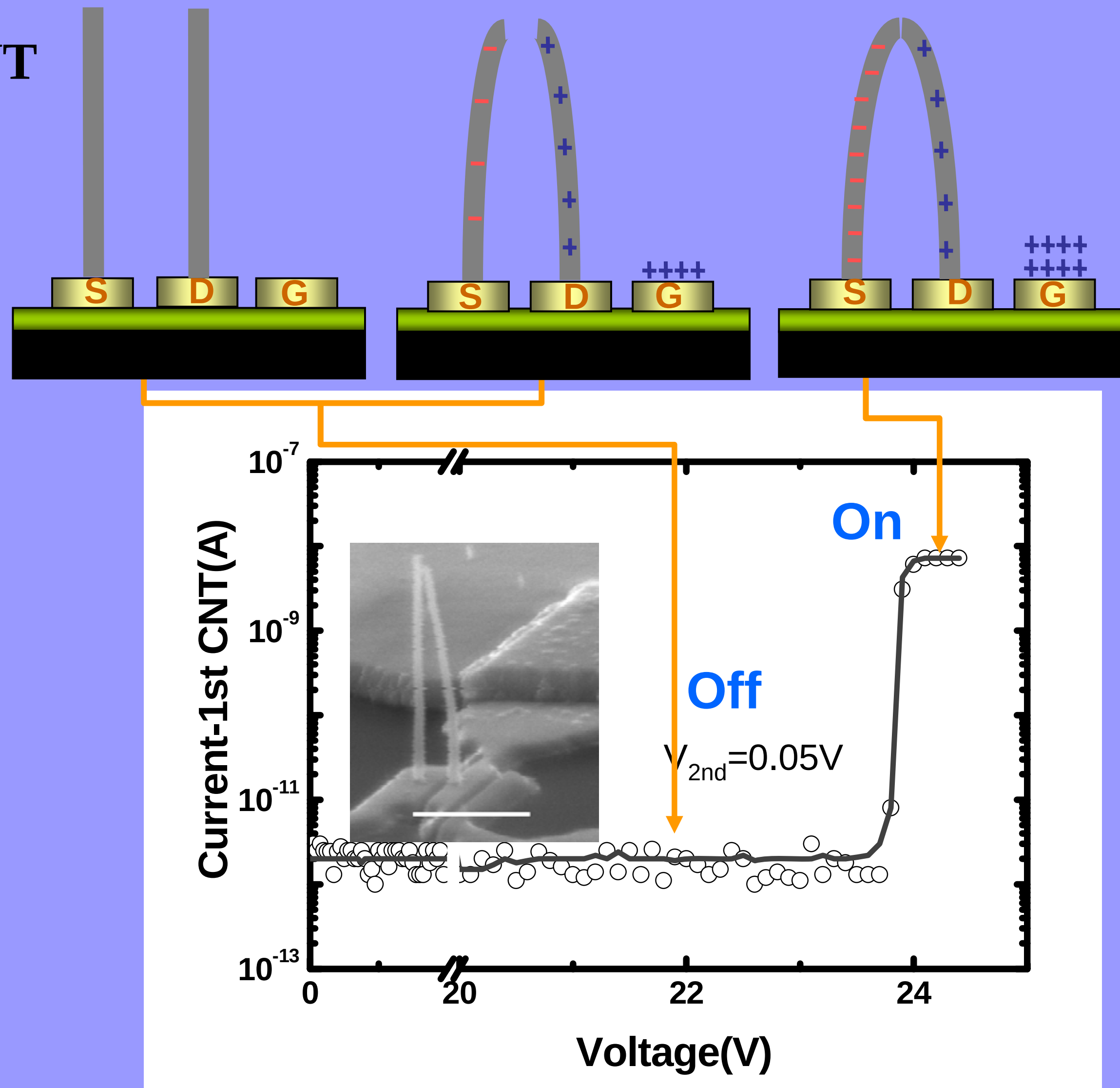
$$f_o \sim \frac{\{E_b(D_o^2 + D_i^2)\}^{1/2}}{L^2 \rho^{1/2}} > 5 \text{ GHz}$$

D_o, D_i :outer & inner diameters
L: suspended nanotube length
E_b: Young's modulus, ρ : density

- The high side gate electrodes balances the van der Waals force enabling nanotubes to remain suspended.

- NEM switch with MWCNT



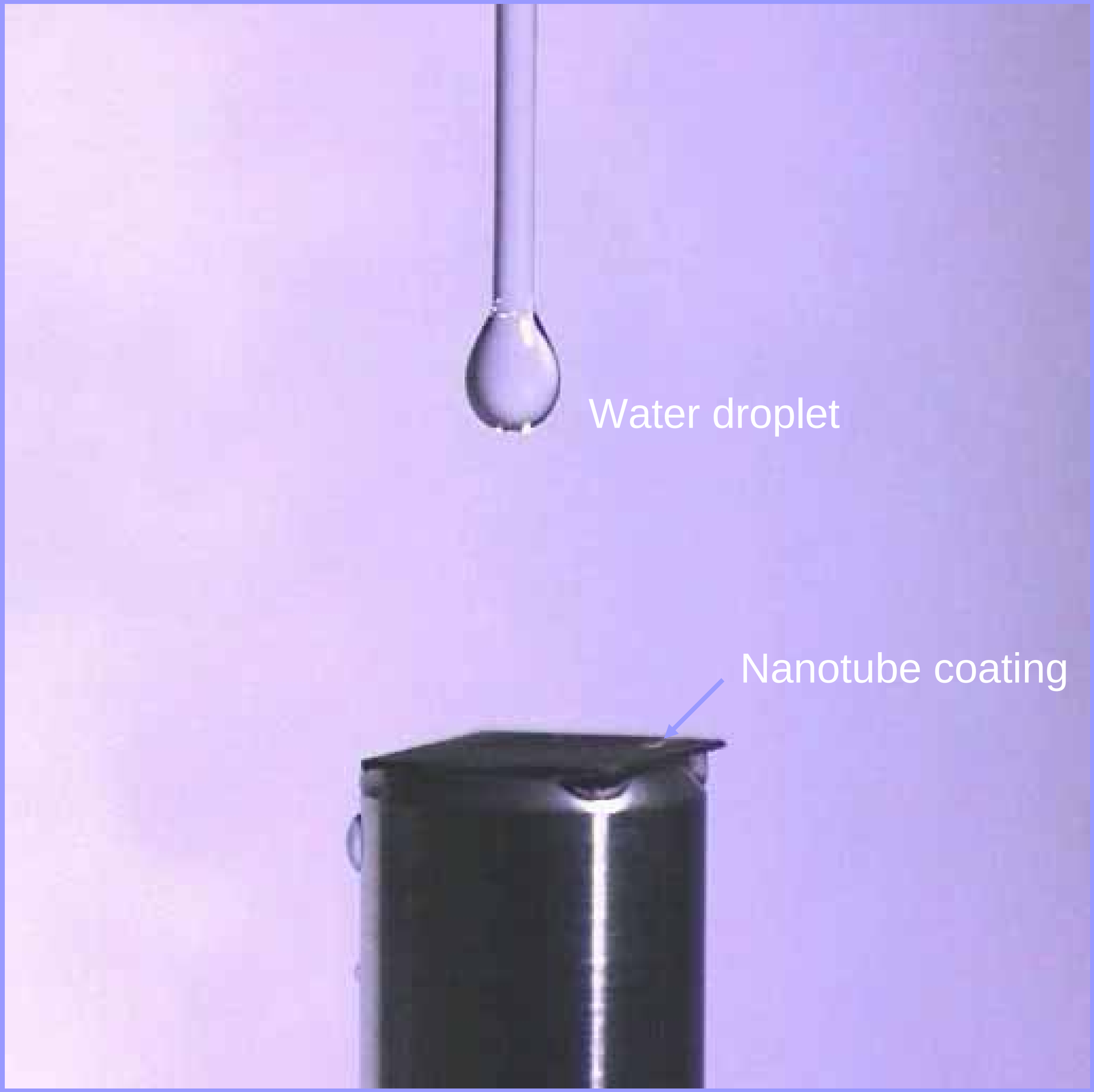


· On & Off state is very clear ; mechanical movement of CNT
· MWCNTs did not return to original position without applied biases

SENSORS

As grown CNTs are hydrophobic but by means of various processes (electrochemical,thermal etc) they can be made hydrophilic. Such hydrophilic CNTs can effectively immobilize antibody which can e.g allow specific bacteria to attach.

Functionalisation of CNTs make them useful as DNA detectors at the sub-attomole level


Water droplet
Nanotube coating

How CNTs may work as gas sensors

- Chemical sensors based on SWCNTs have also been demonstrated- upon exposure to NO_2 or NH_3 the electrical resistance of semiconducting SWCNTS is seen to dramatically alter- v.fast response time
- CNTs that are grown are generally p-type.
- Gases like NO_2 are electrophillic so it can remove electrons from CNTs
- CNT conduction increases and therefore the resistance of the film decreases.

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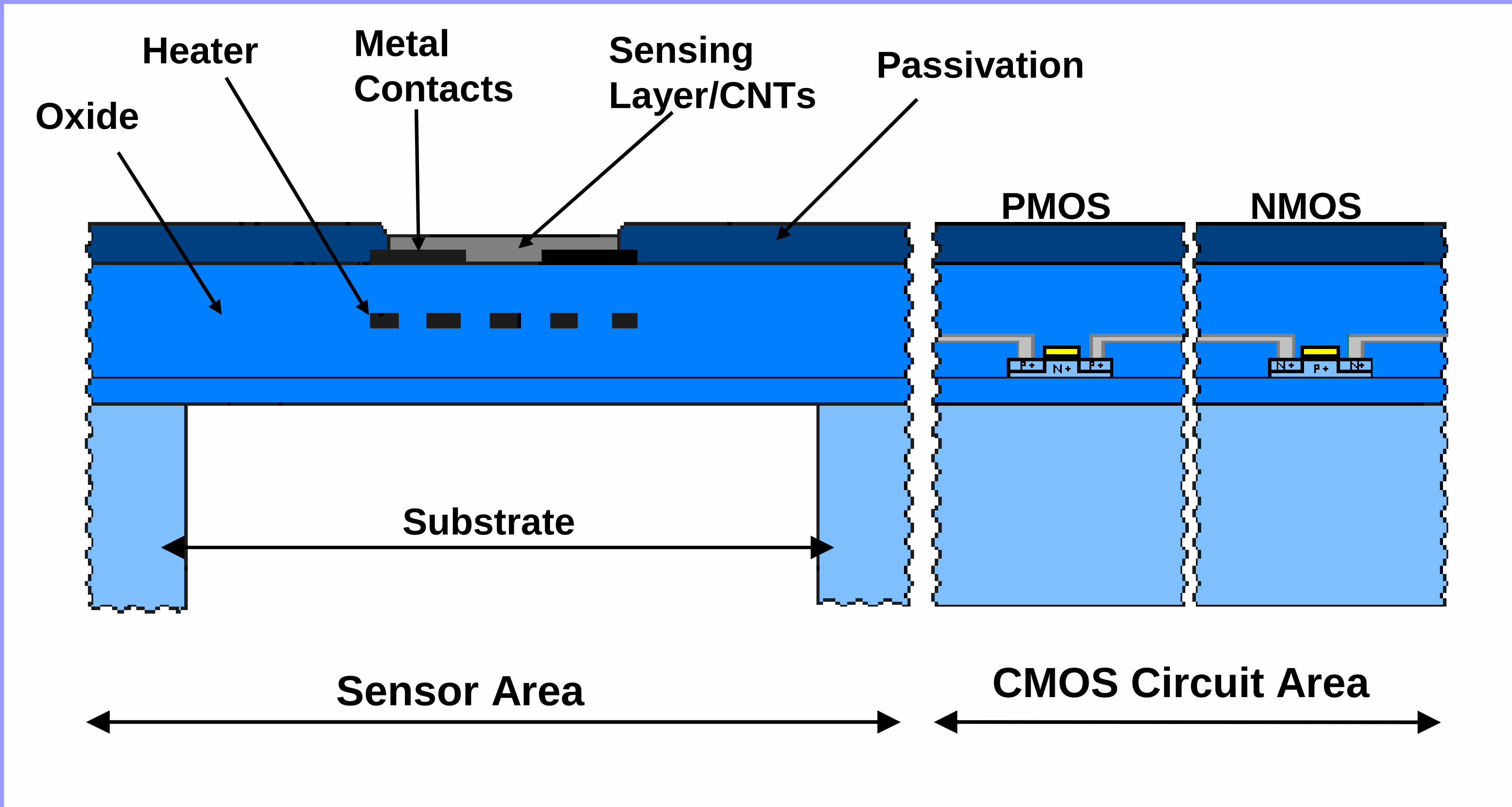
Proposed SOI/CNT Structure



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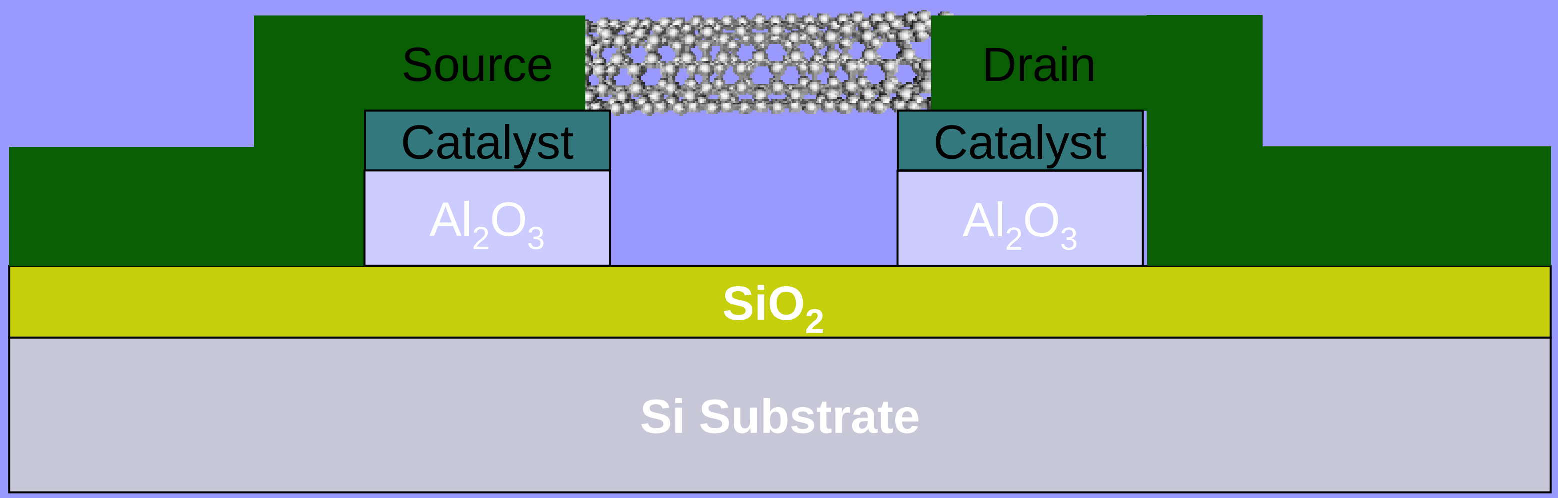
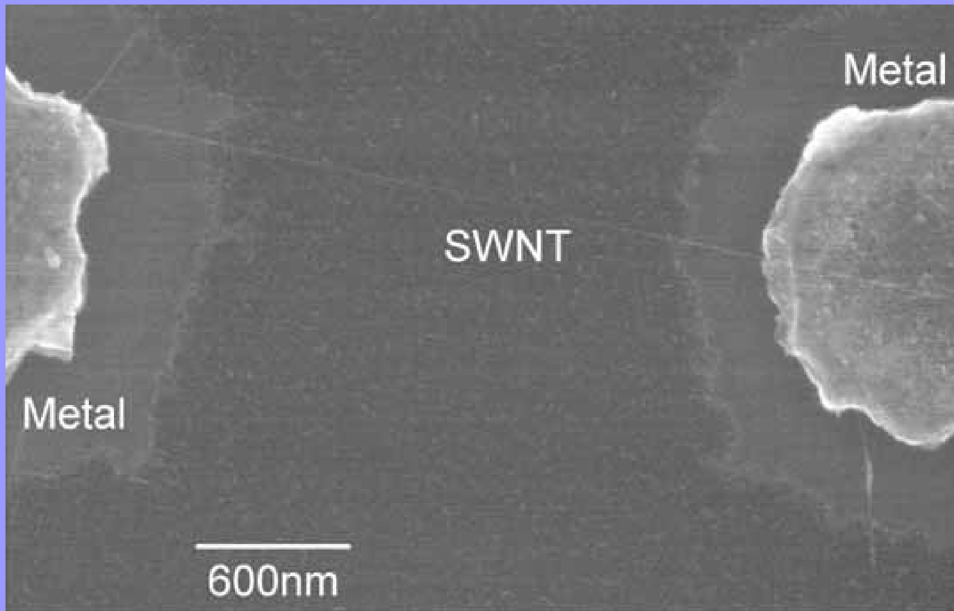
Transistors

Bottom gate transistor fabrication

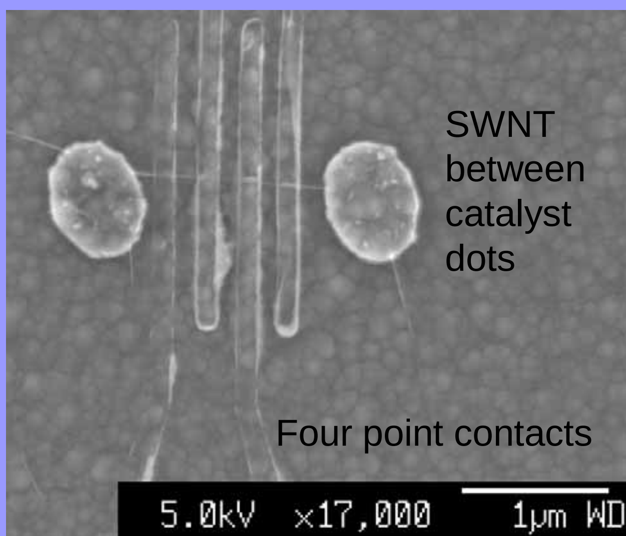


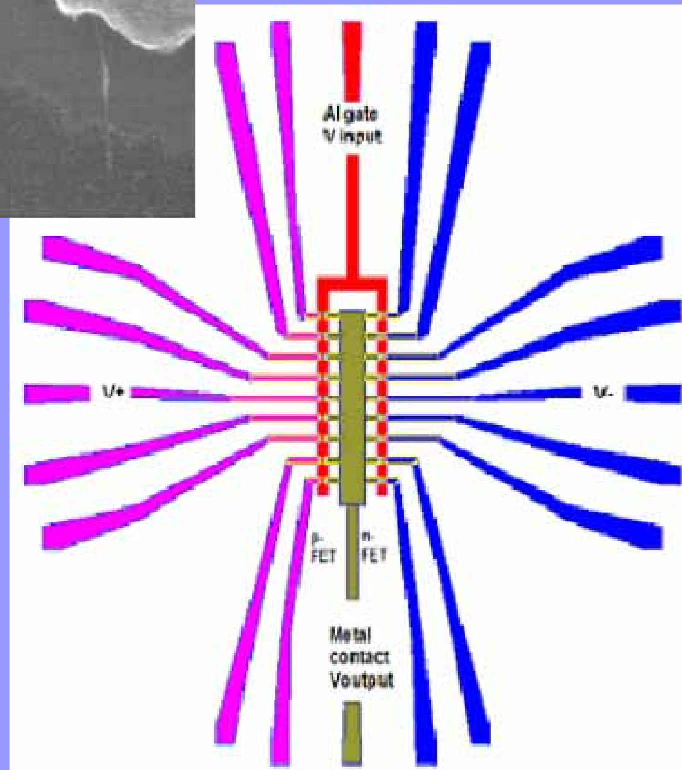
- Concept is to place catalyst dots at known locations
- Dots size and distance are controlled to ensure high yield of SWCNT bridges.
- Only SWCNT which bridge dots are contacted – the rest grow to the SiO_2 substrate

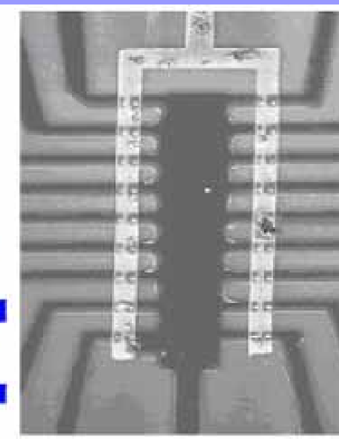
Direct SWNT growth between contacts

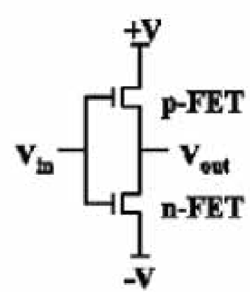


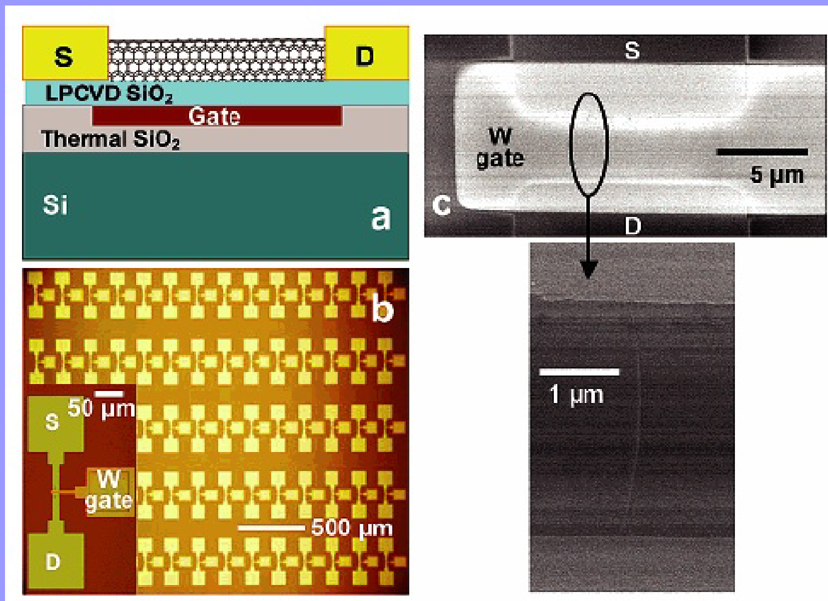
CNT-based logic fabrication






SEM of fabricated device

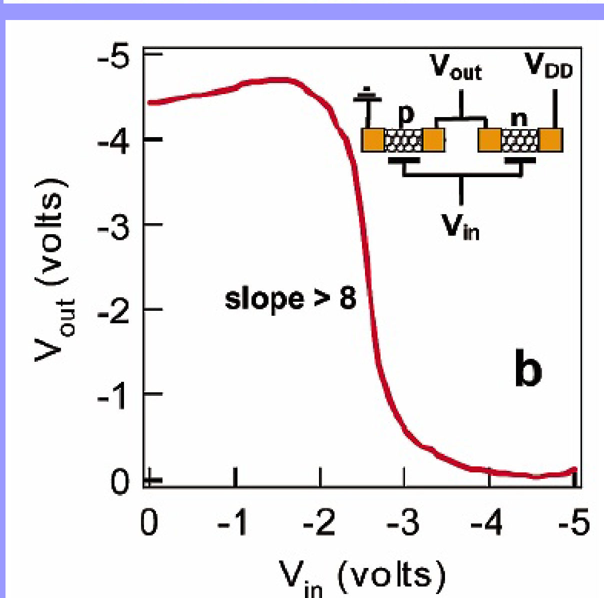


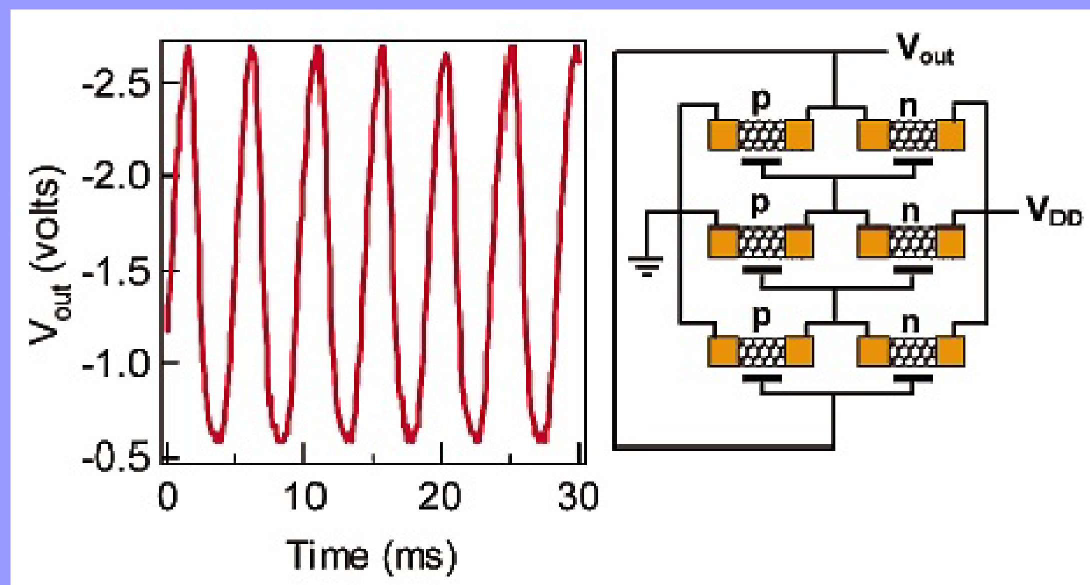


Logic with CNT

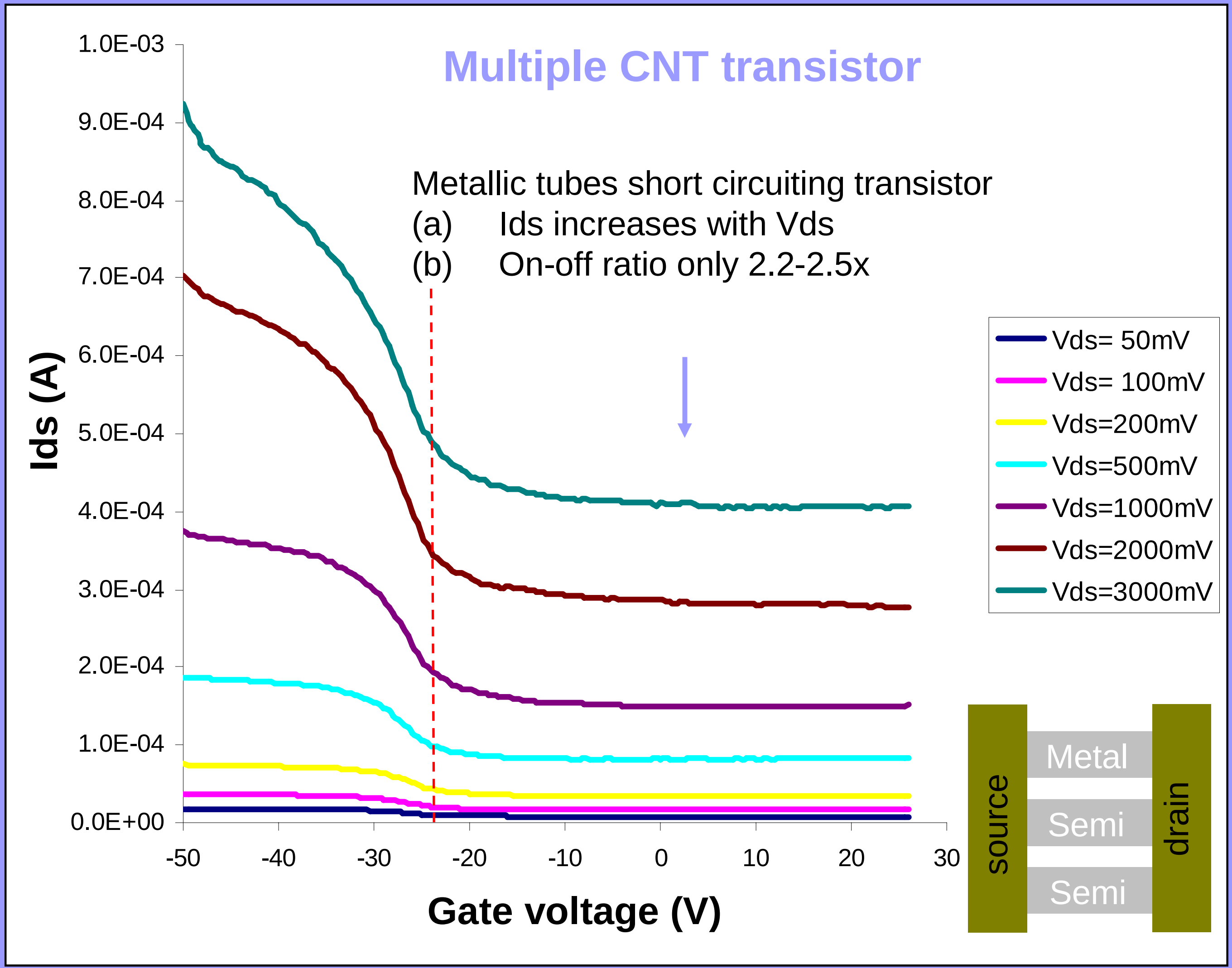
- Simple integration and logic functions demonstrated

  [Javey et al, Nanoletters **2**, 929 (2002)]

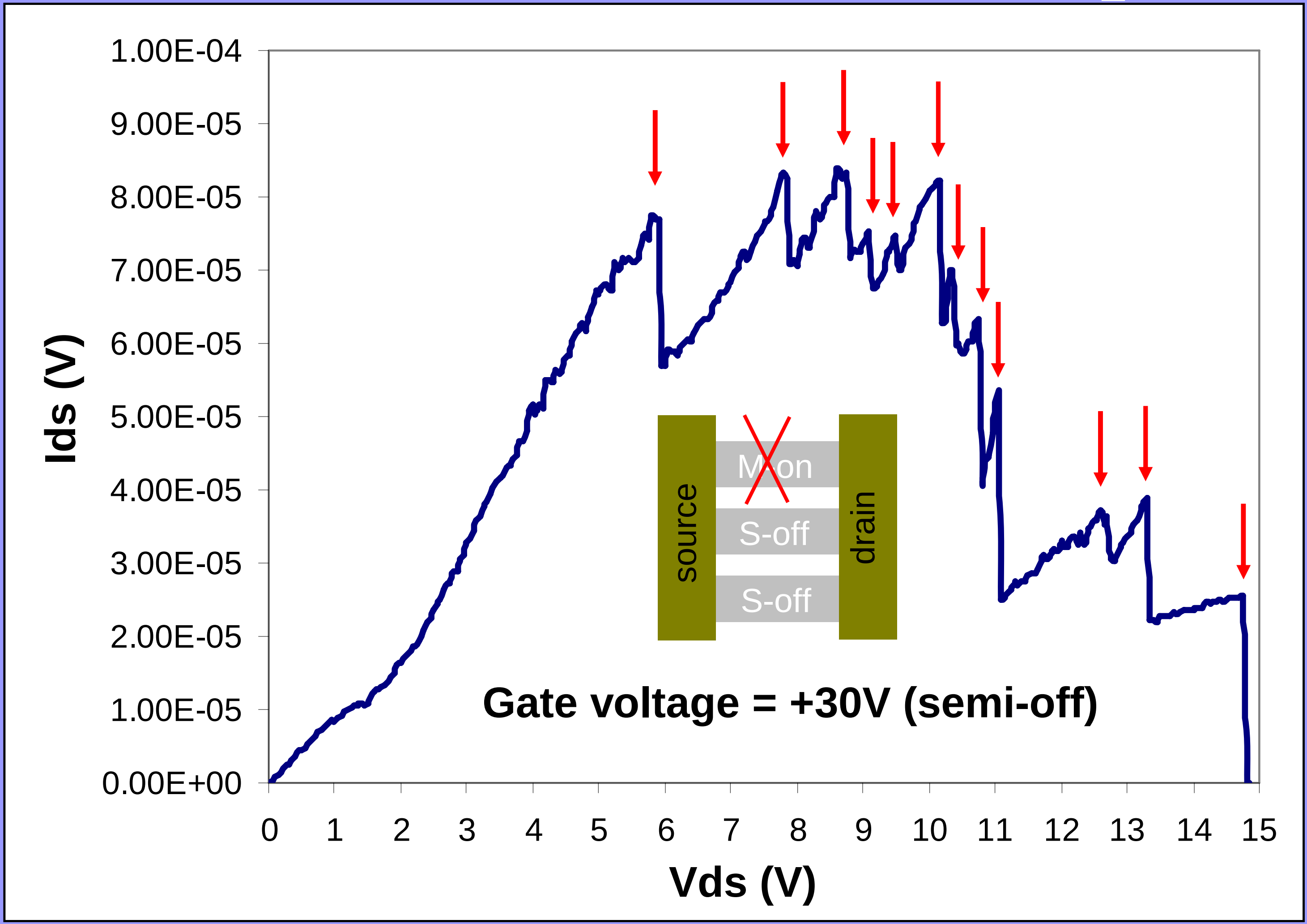




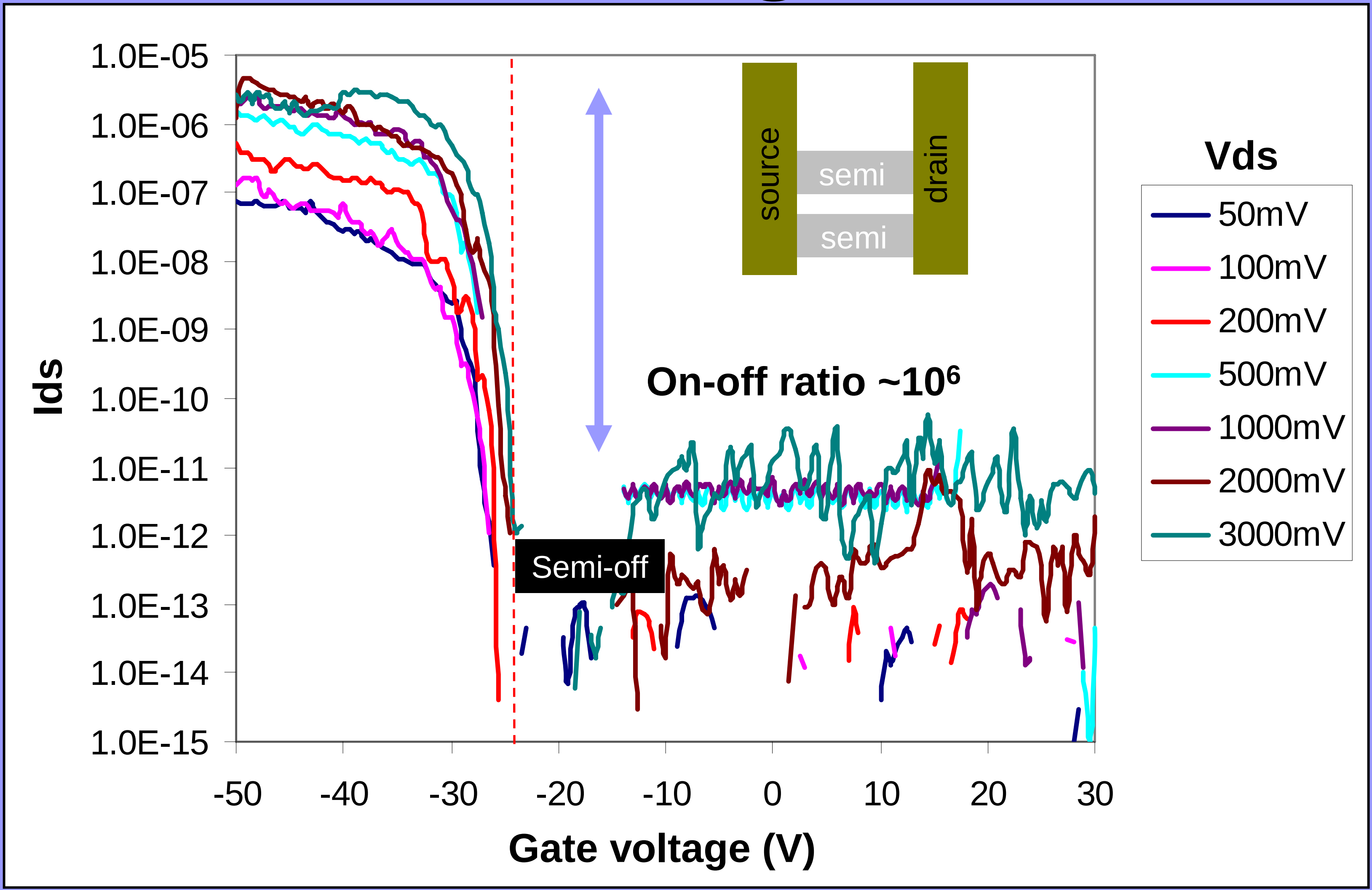
Bottom Gate Transistor Characteristics



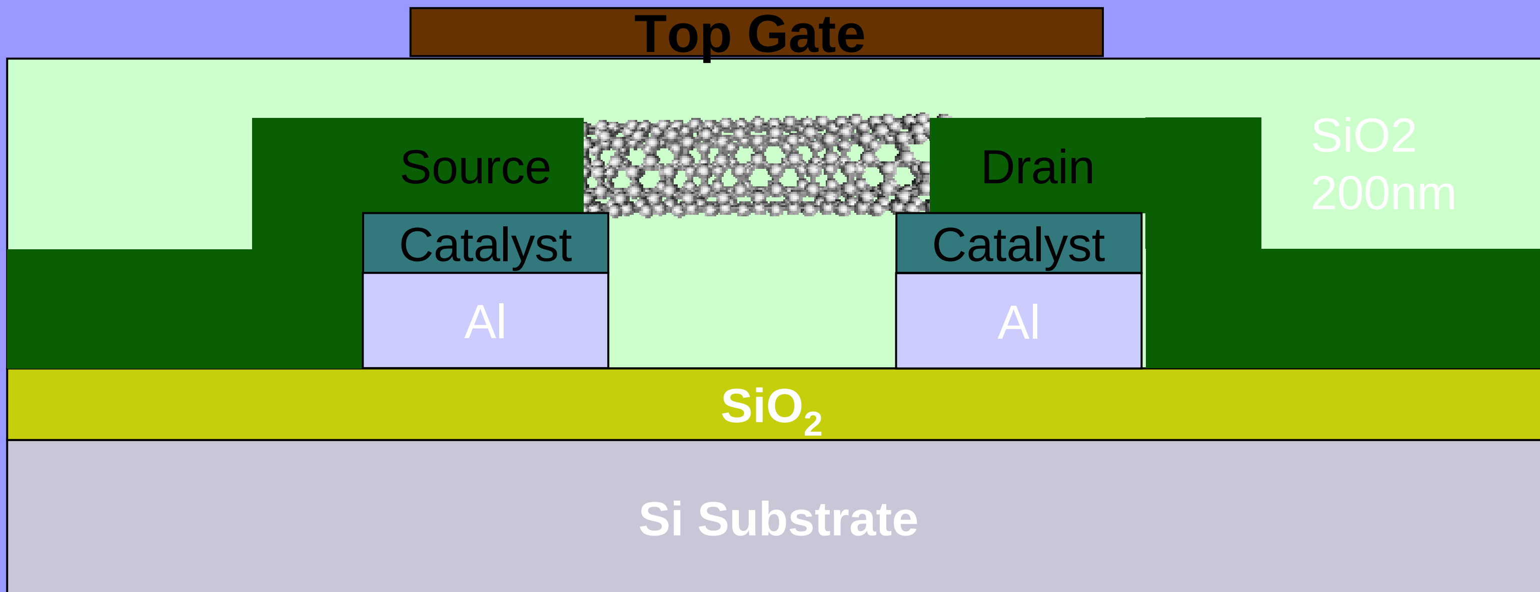
Burn-off metallic SWNTs [IBM]



Semiconducting CNTs left



Top gate transistor fabrication



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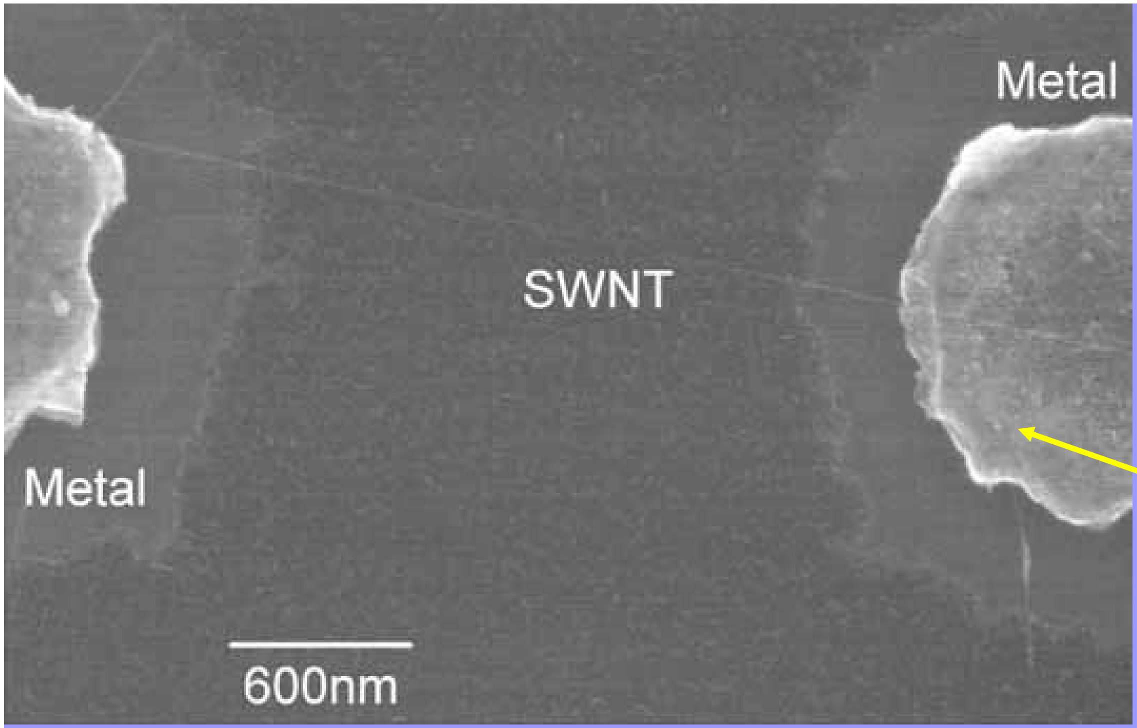
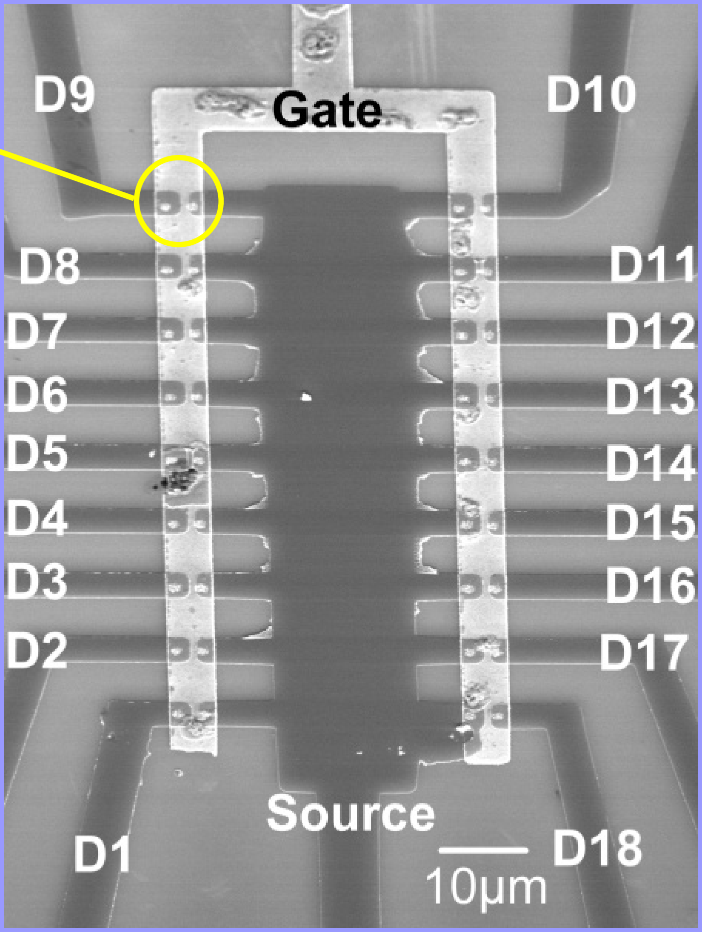
- Dots size and distance are controlled to ensure high yield of SWCNT bridges.
- Only SWCNT which bridge dots are contacted – the rest grow to the SiO_2 substrate

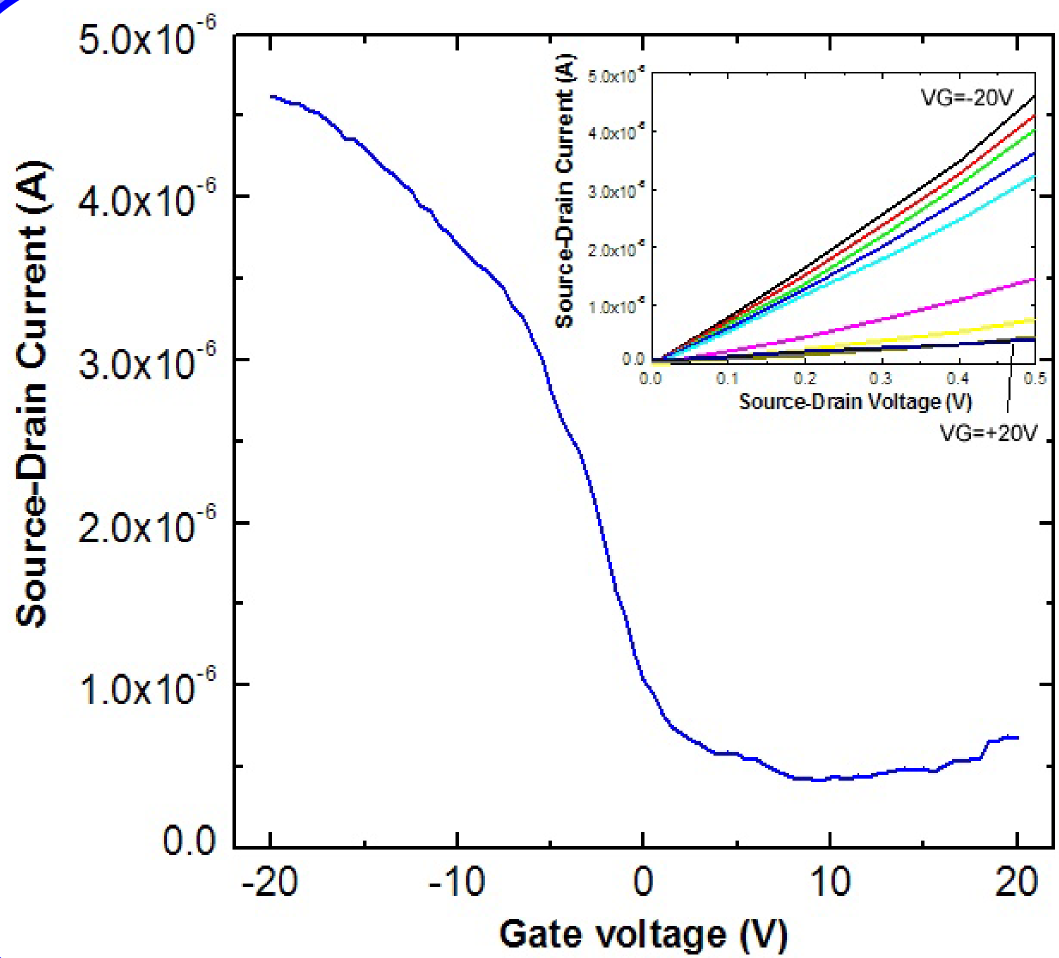


SEM Images of Devices



- ~ 1-3 SWCNT bridging for 1µm dots
- CNT's not bridging grow towards the SiO_2 and are not contacted

Typical Top Gate Transistor Characteristics



- P-type FET response
- On-off ~5-10
- Needs to be pre-burned before top gate fabrication
- Yield 16/18

Conclusions

- Growth of SWCNTs and MWCNTs easy using a variety of methodologies
- Near Term applications dominated by Field Emission properties
- Longer Term applications are many and varied BUT
- Control of Chirality and position vital for further development

Thank you for your attention!

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