Heterogeneous Integration of Single-Walled Carbon Nanotubes with CMOS Circuitry

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Northeastern UNIVERSITY

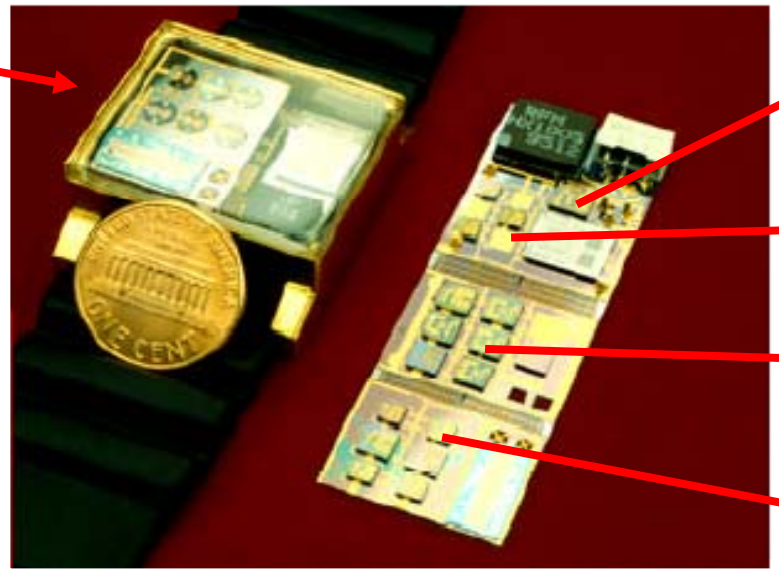
Outline

- Motivation
- Assembly at the Nanoscale
- Integration of SWNTs onto CMOS Circuitry
- I-V Characterization
- Thermal Response
- Gas Response
- Summary

A Multisensor Cluster Prototype for a Generic Microsystem

Multisensor Cluster:

- **High density**
- **Wearable**
- **Low power**



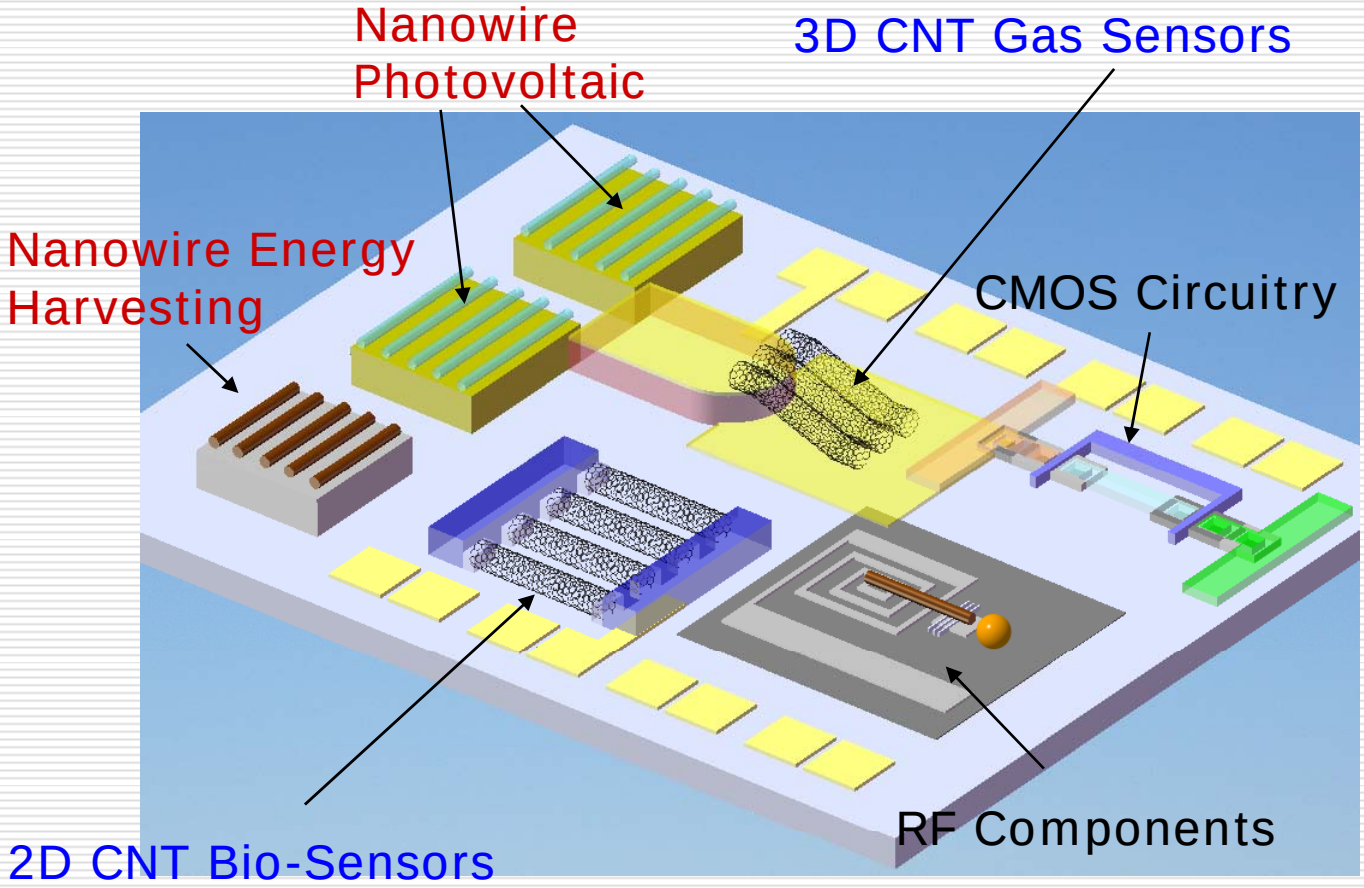
Pressure sensor

Temperature sensor

Humidity sensor

Toxicity

Nanosensor Cluster for Environmental Monitor



-Advantages:

High density

Low power

High sensitivity

Lightweight

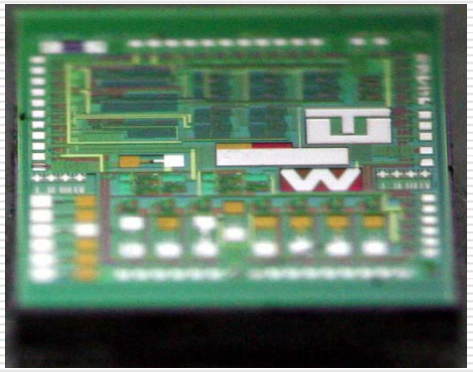
-Applications:

Personal health

Environmental monitor

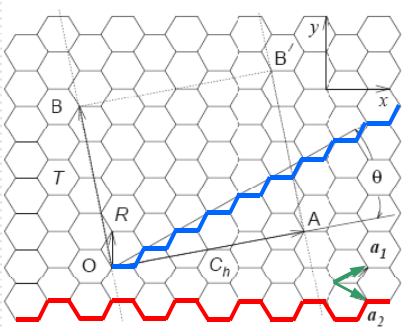
Advantages of Integrating Nano Sensors on CMOS

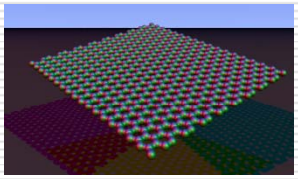
The heterogeneous integration of nanomaterials on to CMOS circuitry have several advantages:



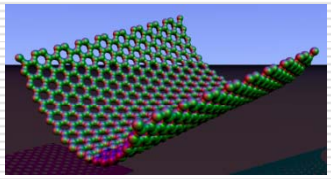
- Miniaturized nanosensor systems
- Reduced cost -one chip system-
- High density multifunctional sensor arrays
- High performance due to reduced parasitic and interconnect lines
- Realization and recording from a massively parallel sensor arrays through electronic circuitry
- This technology is applicable for realizing portable Sensor systems for next generation devices with active nanostructures on CMOS integrated circuits.

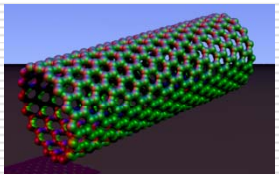
Carbon Nanotubes - Properties





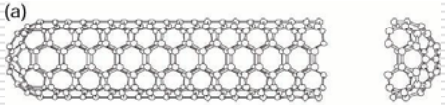
Graphene sheet



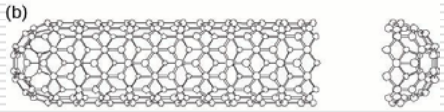


SWNT

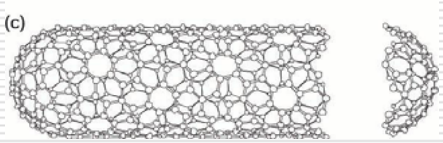
armchair (m, m)



zigzag (n, 0)



chiral (n, m)



Dresselhaus, Carbon, 1995

1) Mechanical Properties

	Young's Modulus (GPa)	Tensile Strength (GPa)	Density (g/Cm^3)
MWNT	1200	~150	2.6
SWNT	1054	75	1.3
SWNT bundle	563	~150	1.3
Graphite (in-plane)	350	2.5	2.6
Steel	208	0.4	7.8

M, O'Connell, Carbon nanotubes, 2006

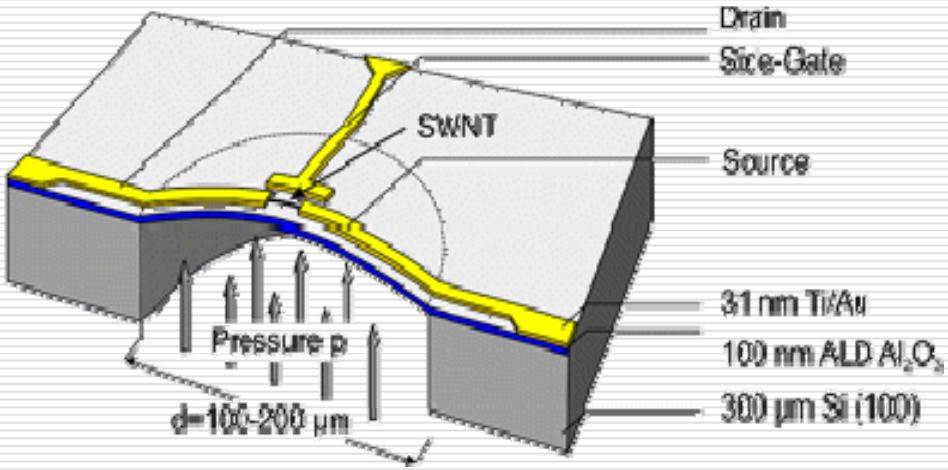
2) Electrical Properties

-Strongly depends on chirality of carbon nanotube

- Ballistic electron transport
- High current density (10^9 Amps/cm^2) ***B.Q. Wei,, Appl. Phys. Lett. 2001***
- Band gap for Semiconducting CNTs scale inversely with the diameter of the tube (E_g = 0.84 eV/d [nm]) ***M, O'Connell, Carbon nanotubes, 2006***

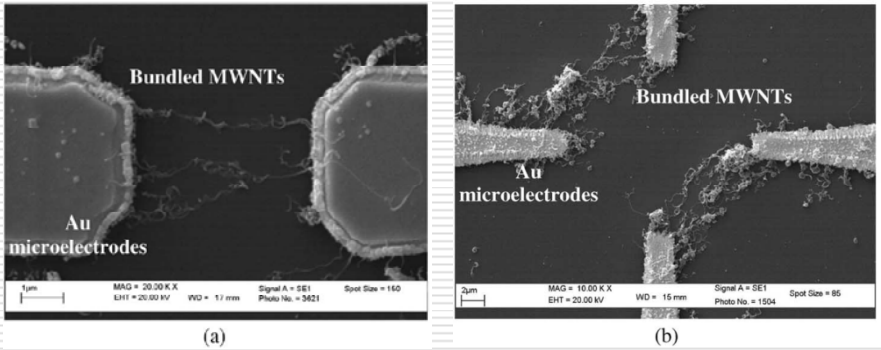
Applications of Carbon Nanotubes - Sensors -

Pressure Sensors:



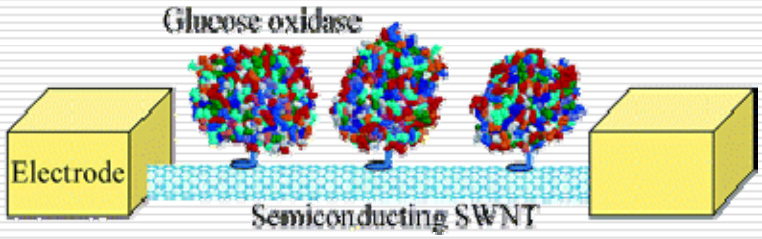
Stampfer, Nano Letts., 2005

Thermal Sensors:



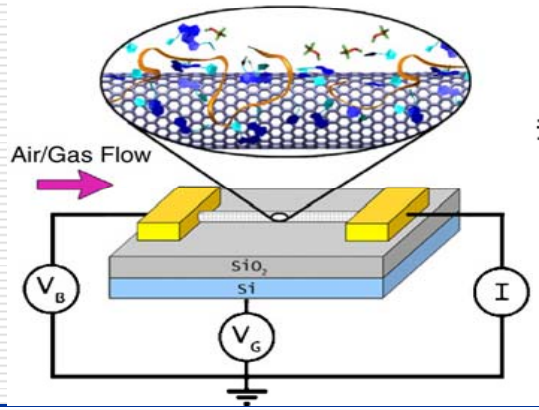
Fung, IEEE-Nano, 2004 and Chan, Nanotechnology, 2004

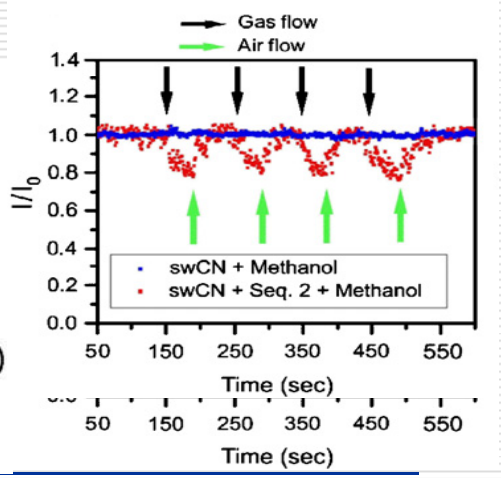
BioSensors:



Besteman, Nano Letts., 2003

Gas Sensors:

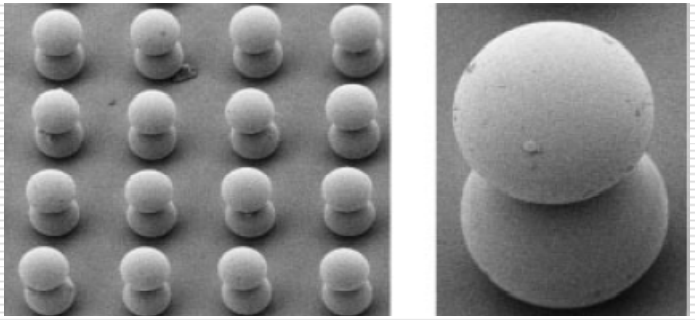




Staii, Nano Letts., 2005

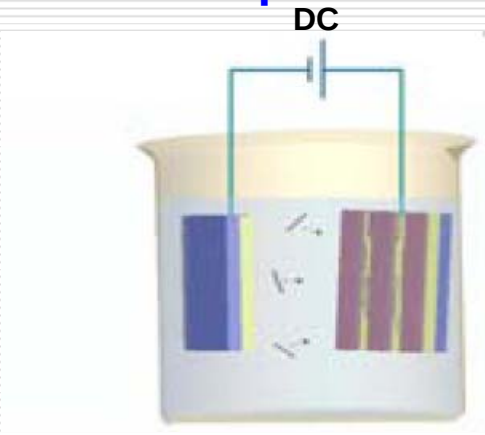
Nanoscale Assembly

Self Assembly

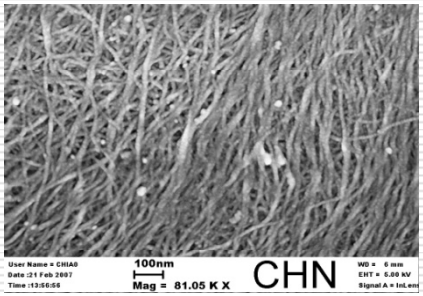


Tobias et al., Adv. Mater., 2005

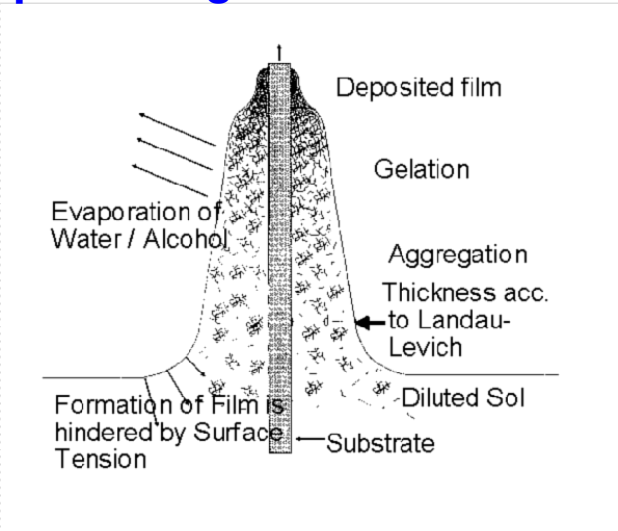
Electrophoresis



Drop Casting

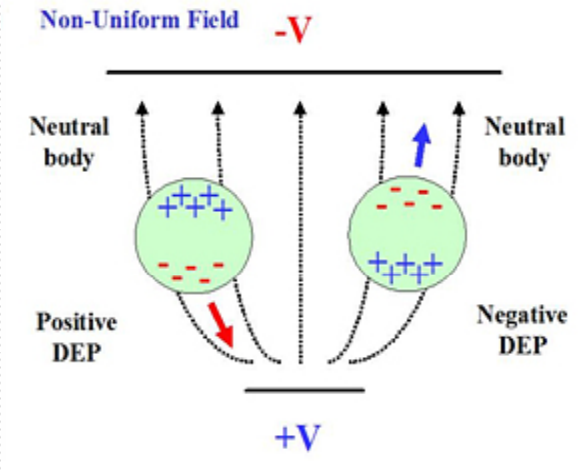


Dip Coating

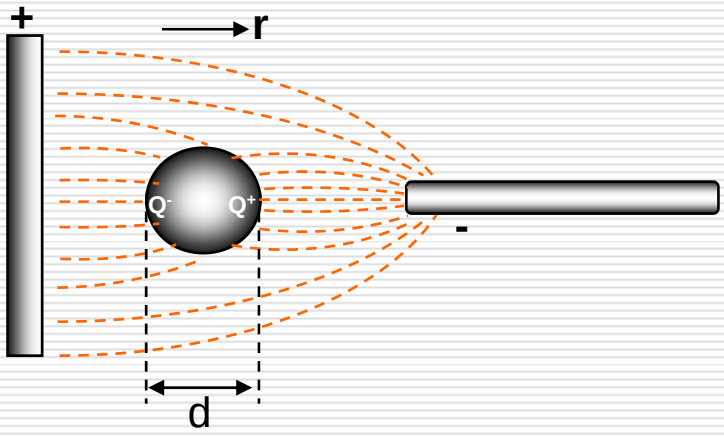


Brinker, *J. Phys. III France, 1994*

Dielectrophoresis

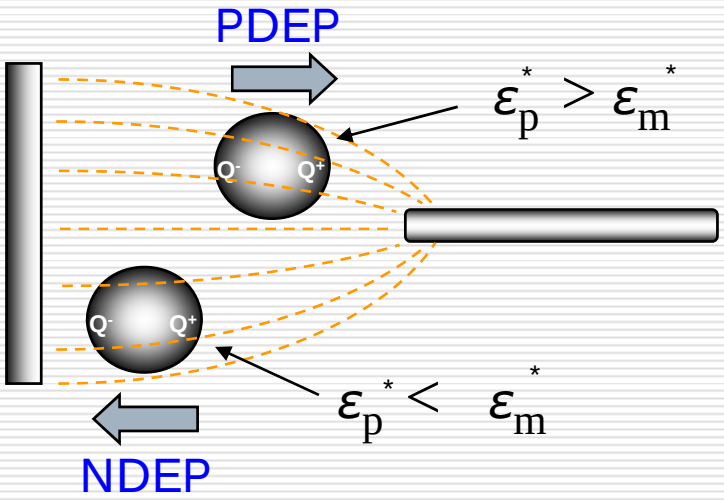


Dielectrophoretic (DEP) Assembly



Apply DC electric field:

$$F = (m \cdot \nabla)E$$



Apply AC electric field:

$$F_{DEP} = 2\pi\varepsilon_0\varepsilon_r r^3 \operatorname{Re}[K(\omega)]\nabla E^2$$

$$K(\omega) = \left[\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*}\right]$$

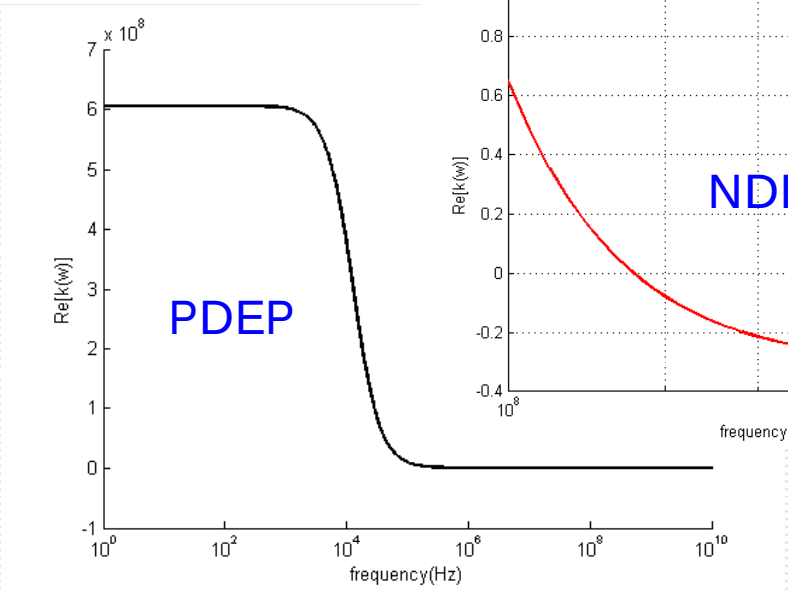
Clausius-Mossotti factor:
depends on the relative permittivity of the particles and medium

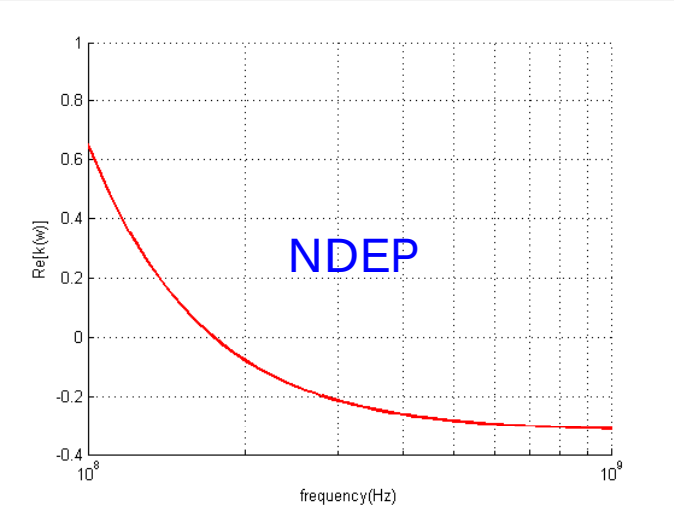
Clausius-Mossotti Factor

For SWNTs

$$K(\omega)=\left[\frac{\varepsilon_p^*-\varepsilon_m^*}{3\varepsilon_m^*}\right]$$

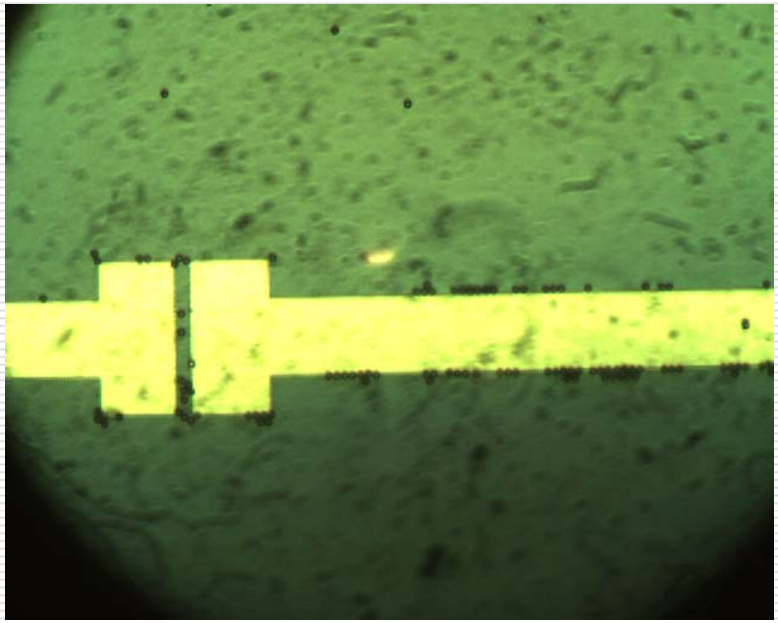
$$\varepsilon_p^*=\varepsilon_p-\frac{j\sigma_p}{\omega},\ \varepsilon_m^*=\varepsilon_m-\frac{j\sigma_m}{\omega}$$





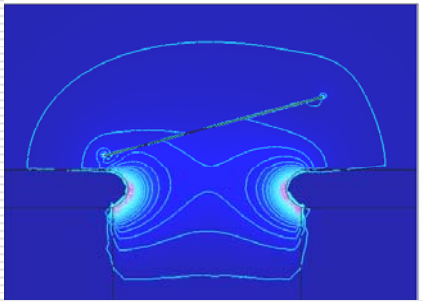
ε_p=2.5 ε_0, σ_p=10^5 and ε_m=78.36 ε_0,
σ_m=5.5x10^{-6}

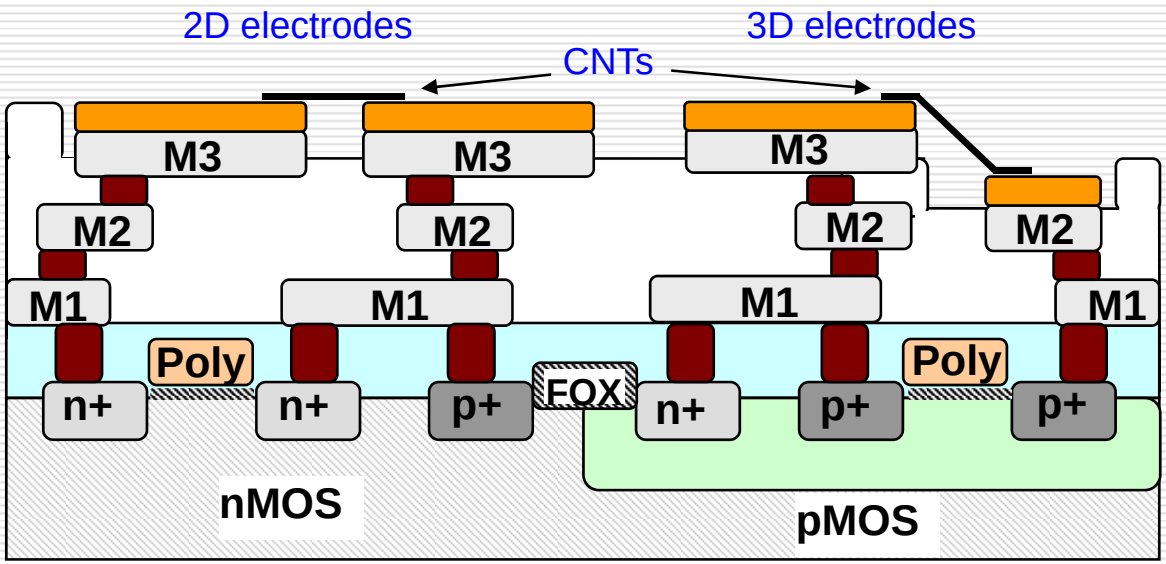
Positive and Negative DEP

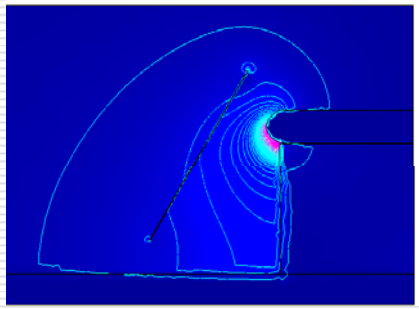


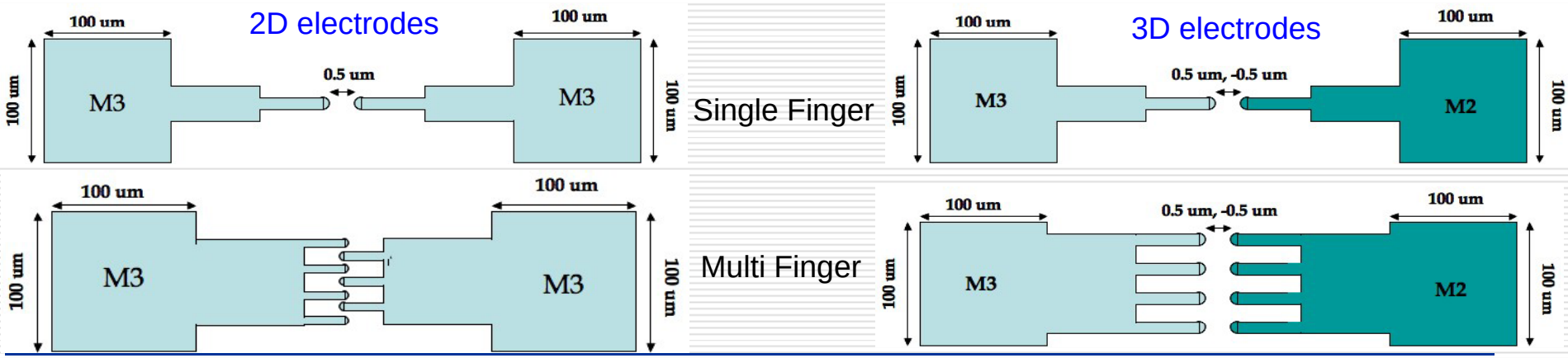
10µm particles
frequency is varied from
10KHz-100KHz-10KHz

Electrode Design for Low Voltage DEP Assembly of Nanotubes









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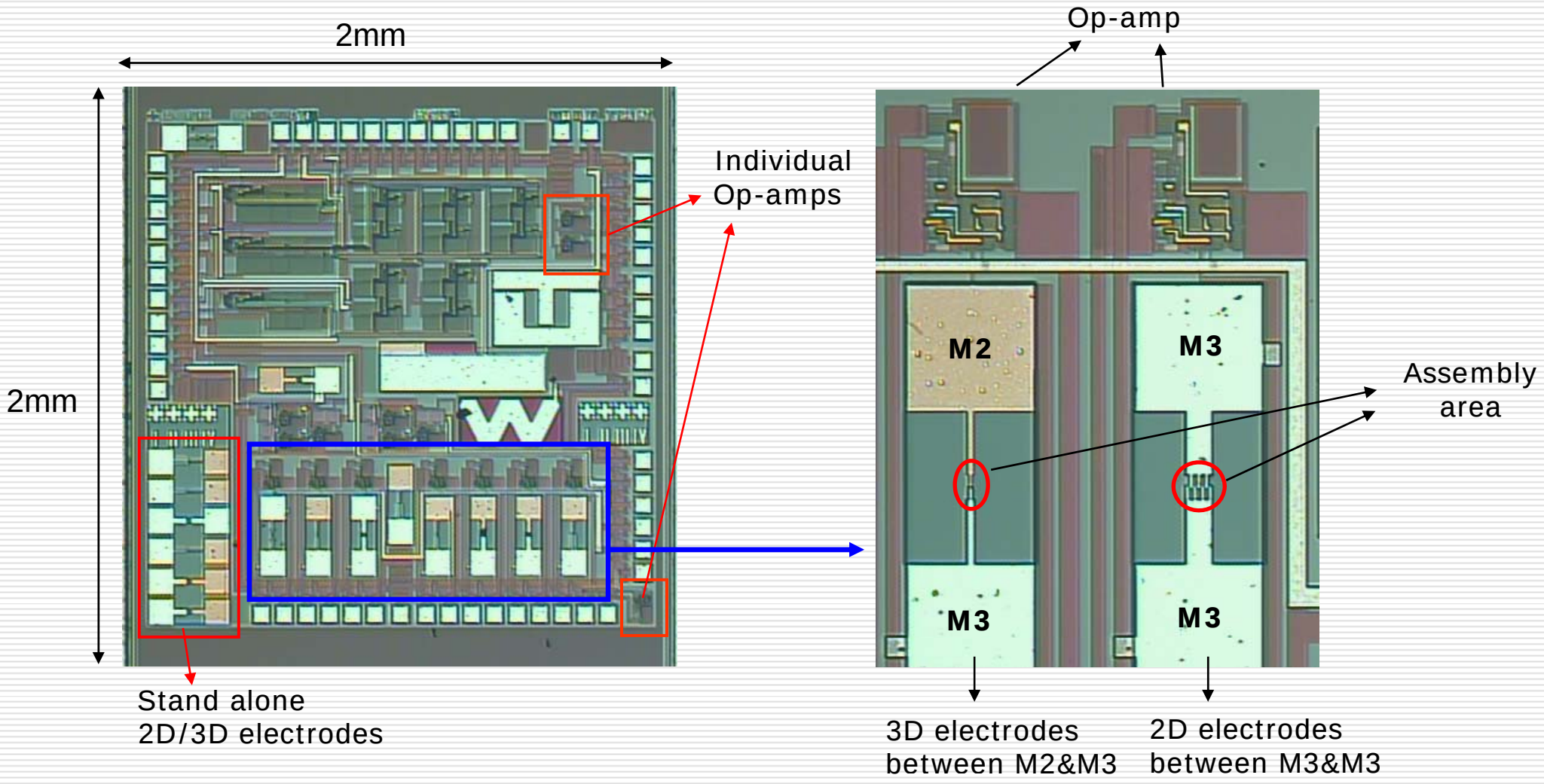
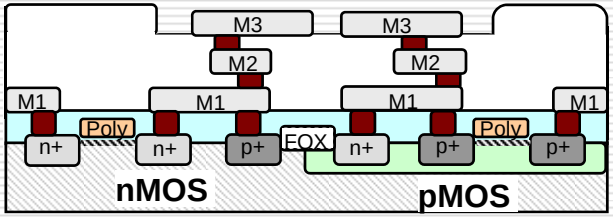
Chip Design (AMI 0.5 um CMOS technology)

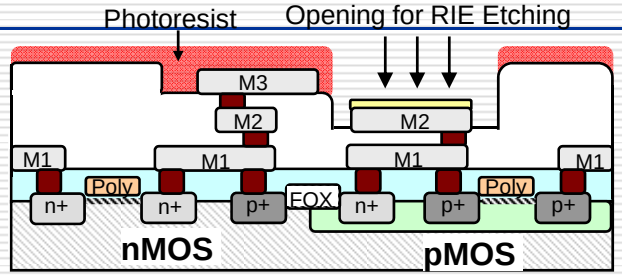


Fabrication Process

2D CNT Assembly

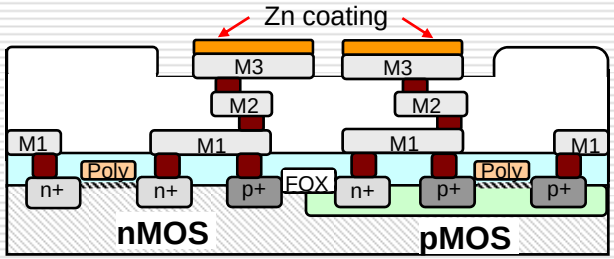


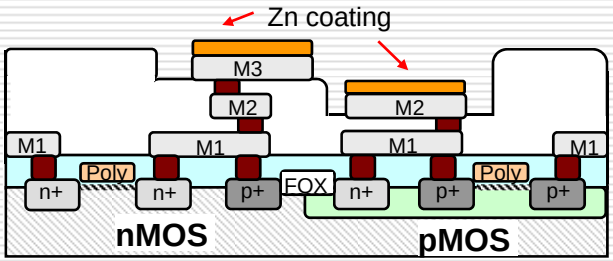
Fabricated CMOS die



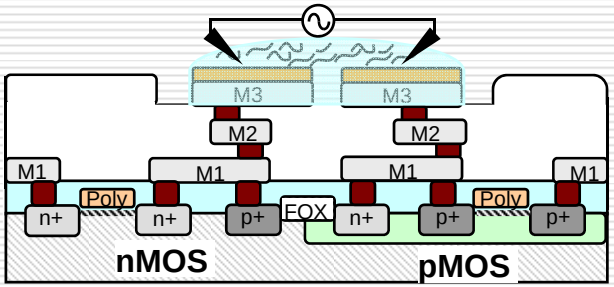
3D CNT Assembly

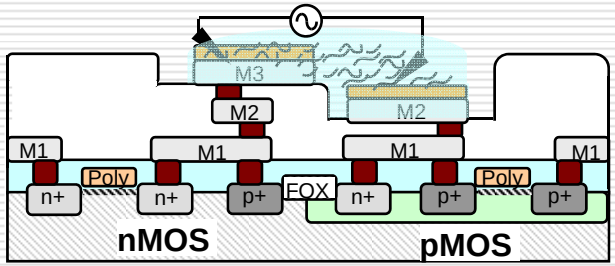
Electroless Zincation



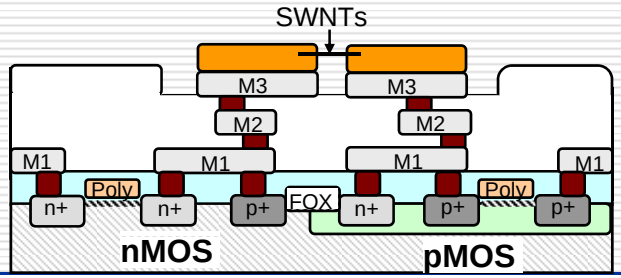


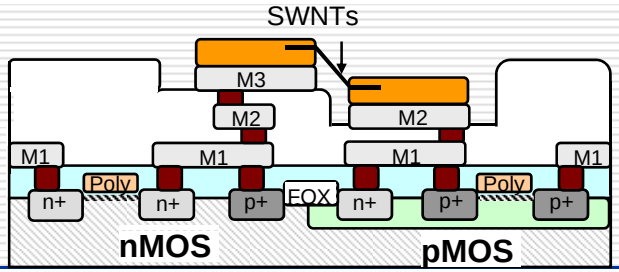
DEP Assembly



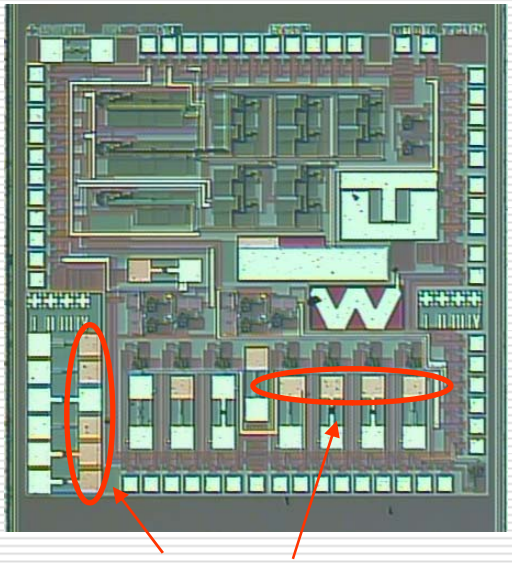


2nd zincation process



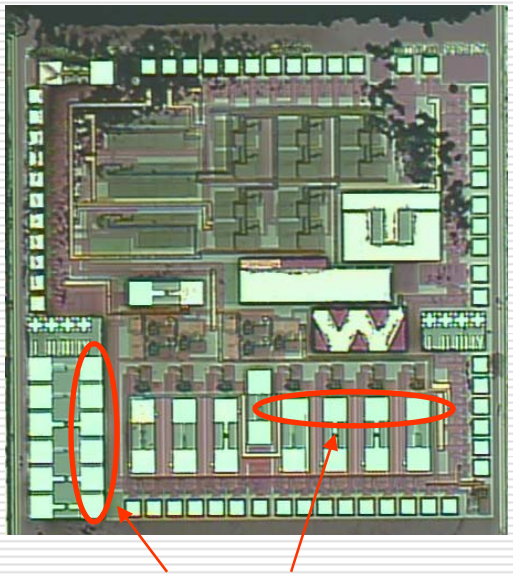


Post CMOS Fabrication



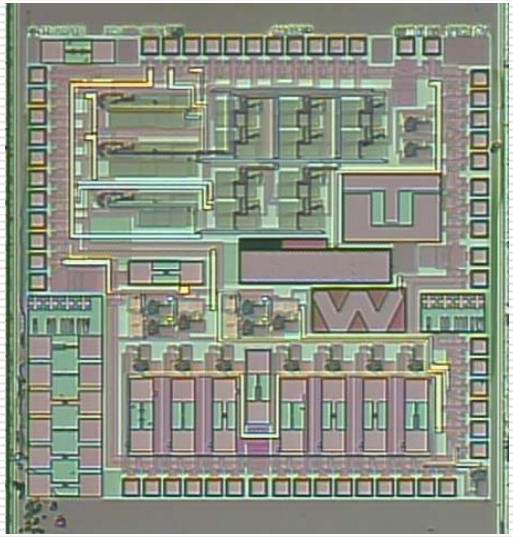
Residue

RIE



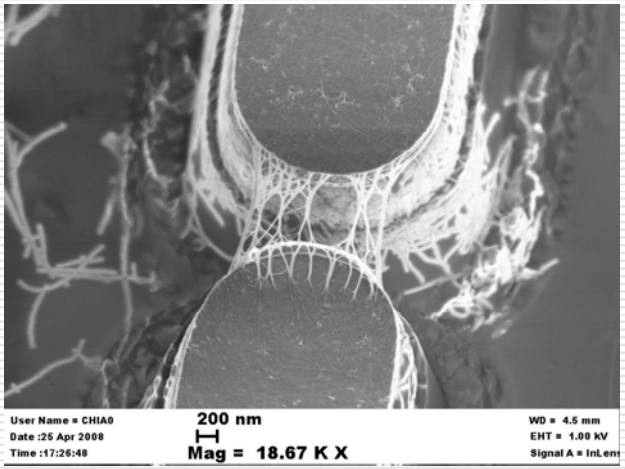
Residue is removed

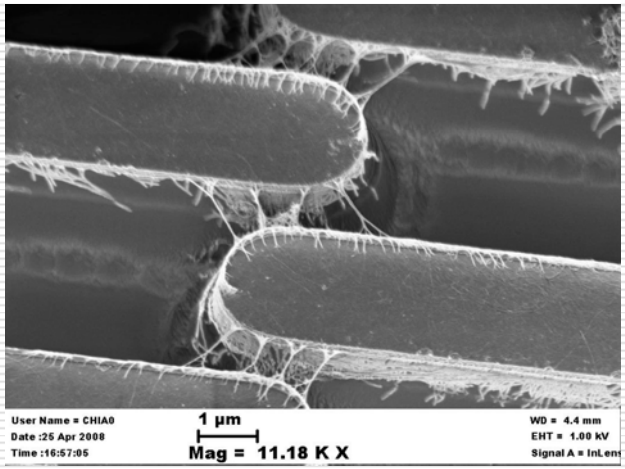
Zincation

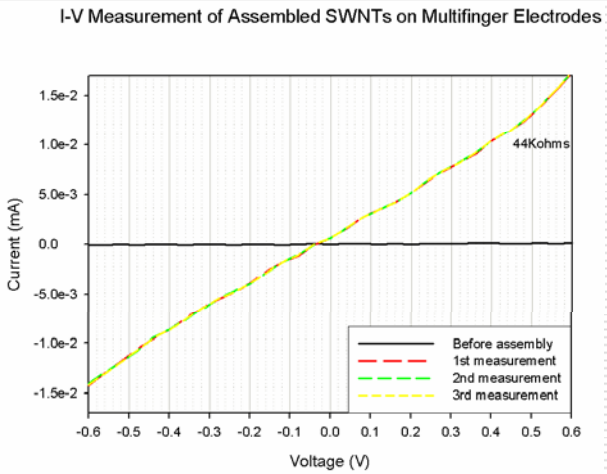


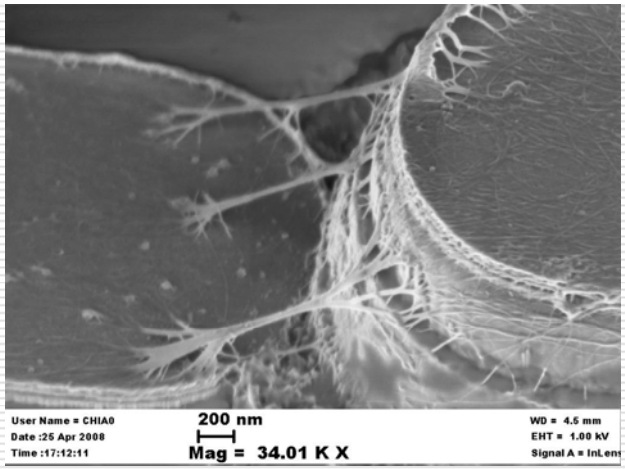
All Al electrodes are covered by a Zinc layer

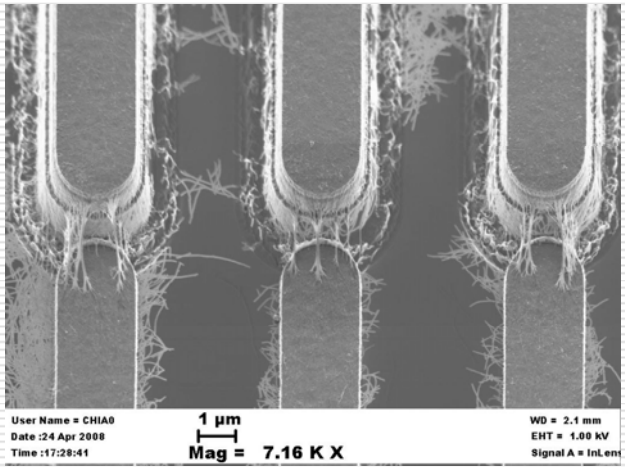
SEM Imaging and I-V Measurements

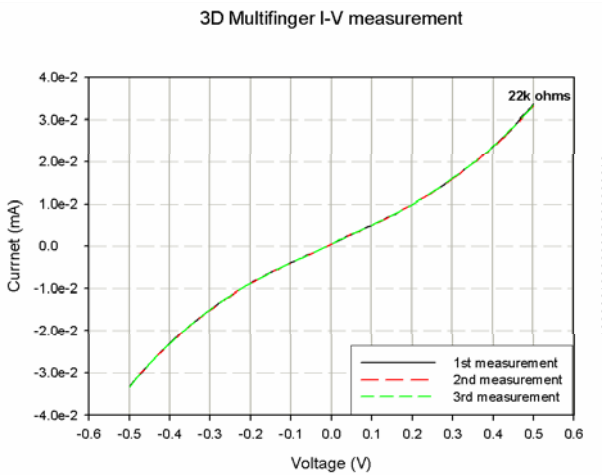




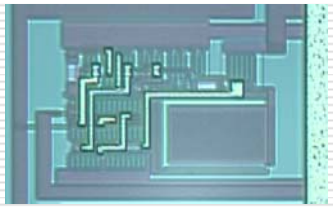


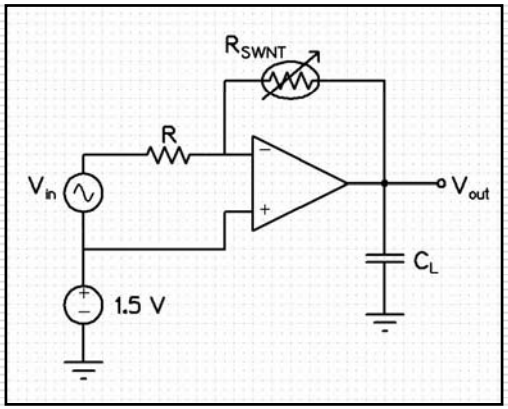






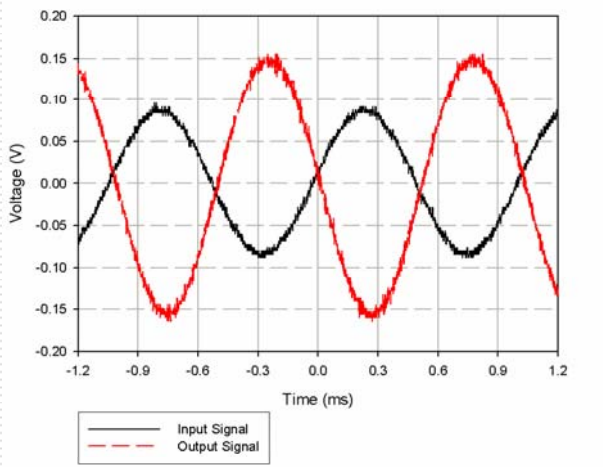
CMOS Readout Circuitry

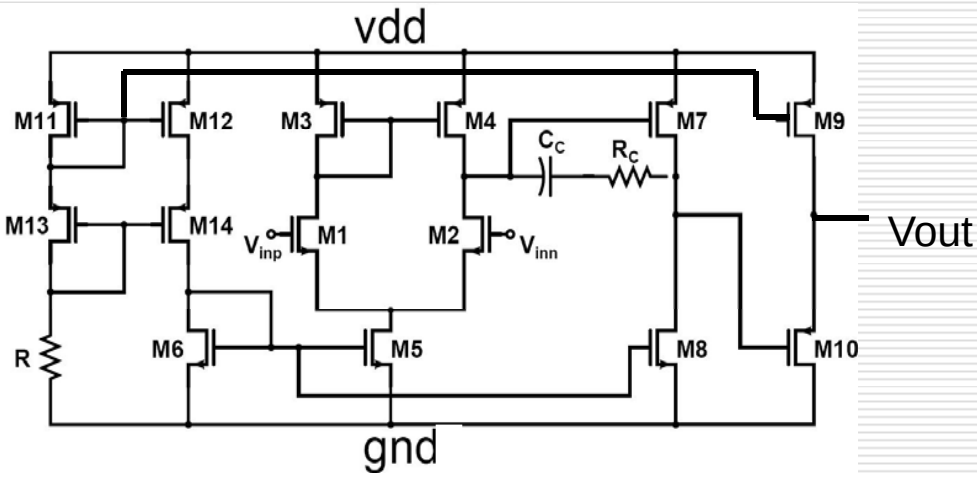




Inverting Operational Amplifier

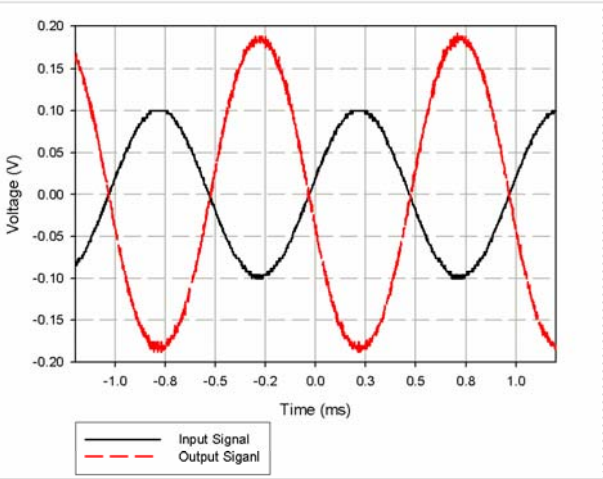
2D electrodes





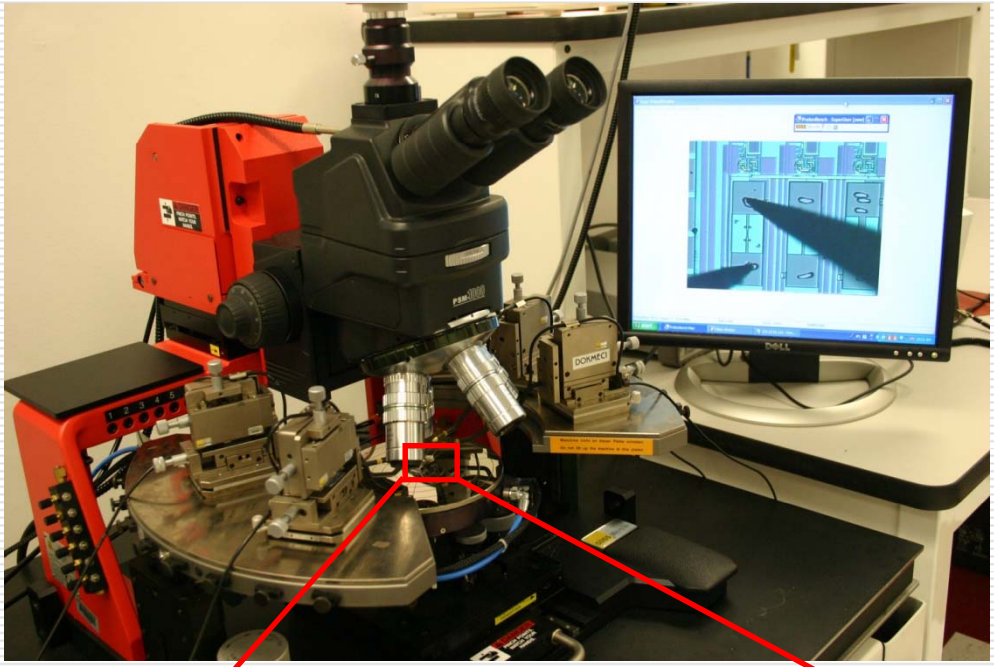
Schematic of Operational Amplifier

3D electrodes

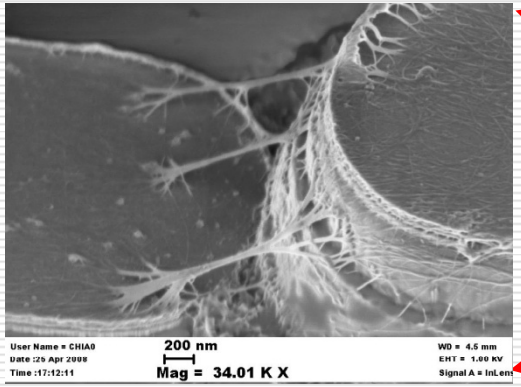


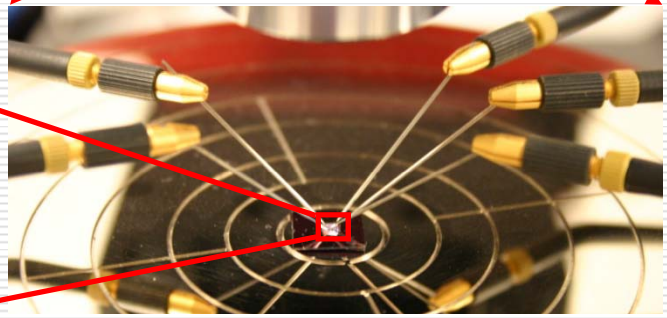
Measurement Setup for Thermal Sensor

Temperature Controller



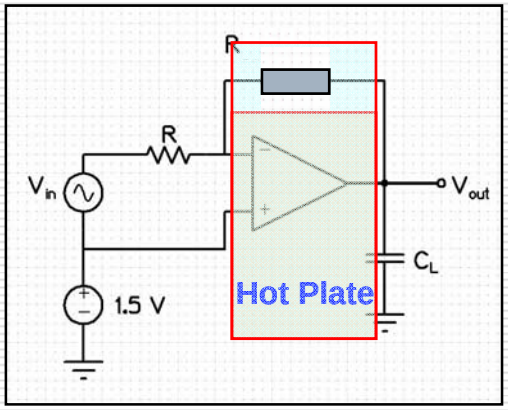
SWNTs based Thermal Sensor integrated onto CMOS Circuitry



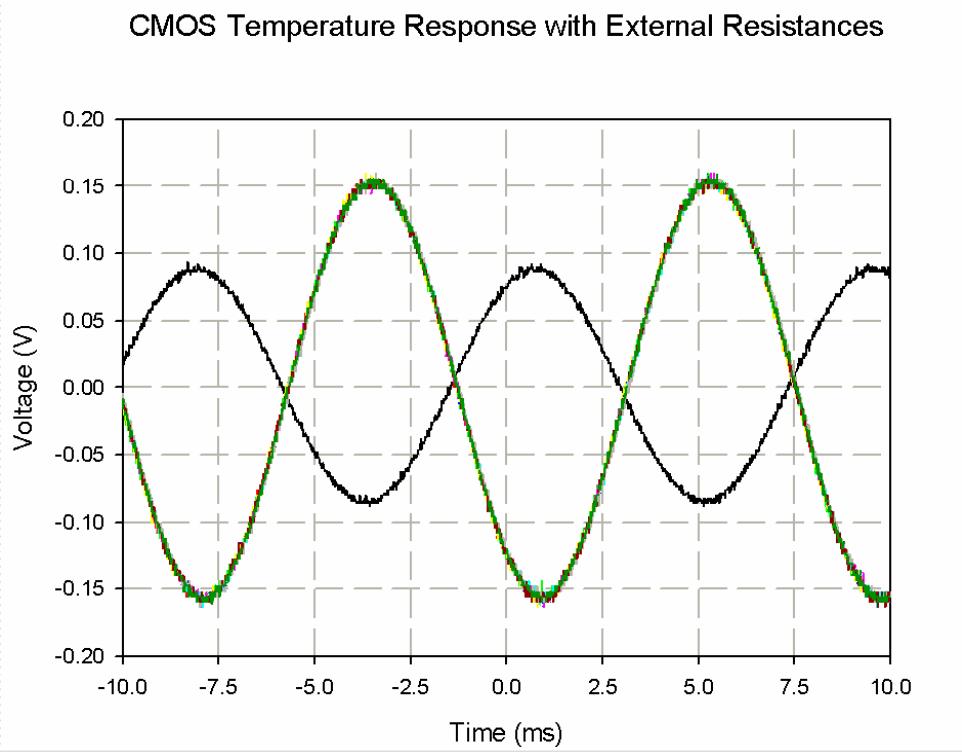


Heatable Chuck

Temperature Response of the CMOS chip with an External Resistor



Inverting Operational Amplifier

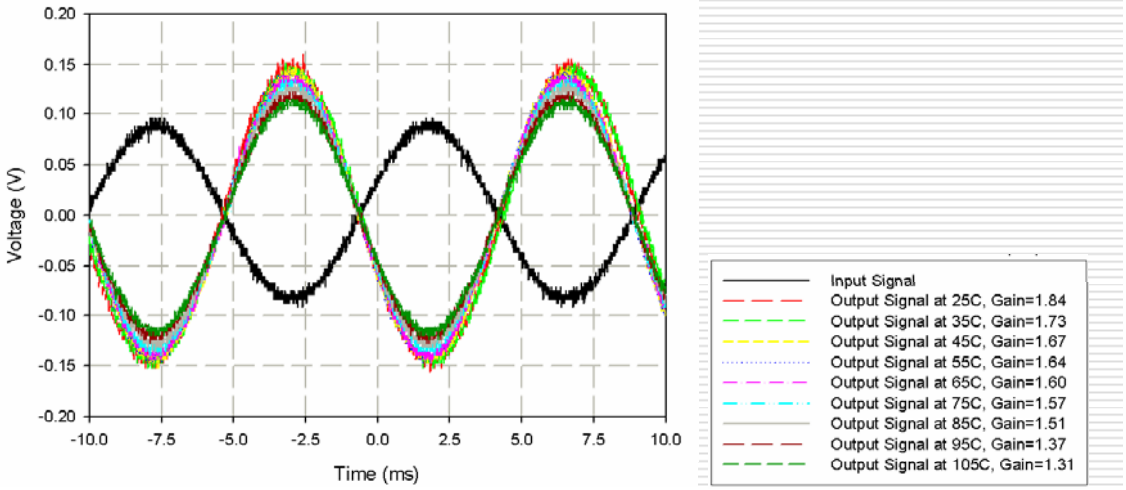


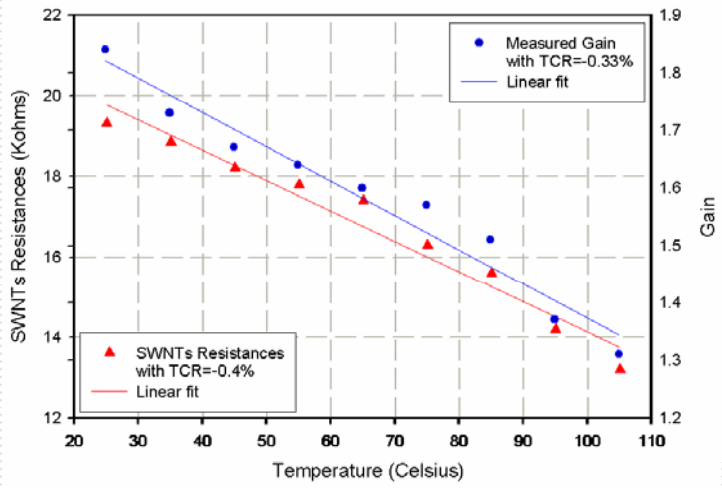
- Input Signal
- Output Signal at 25C, Gain= 1.8
- Output Signal at 35C, Gain= 1.8
- Output Signal at 45C, Gain= 1.8
- Output Signal at 55C, Gain= 1.8
- Output Signal at 65C, Gain= 1.8
- Output Signal at 75C, Gain= 1.8
- Output Signal at 85C, Gain= 1.8
- Output Signal at 95C, Gain= 1.8
- Output Signal at 105C, Gain= 1.8

Thermal Response of SWNTs integrated on CMOS Circuitry

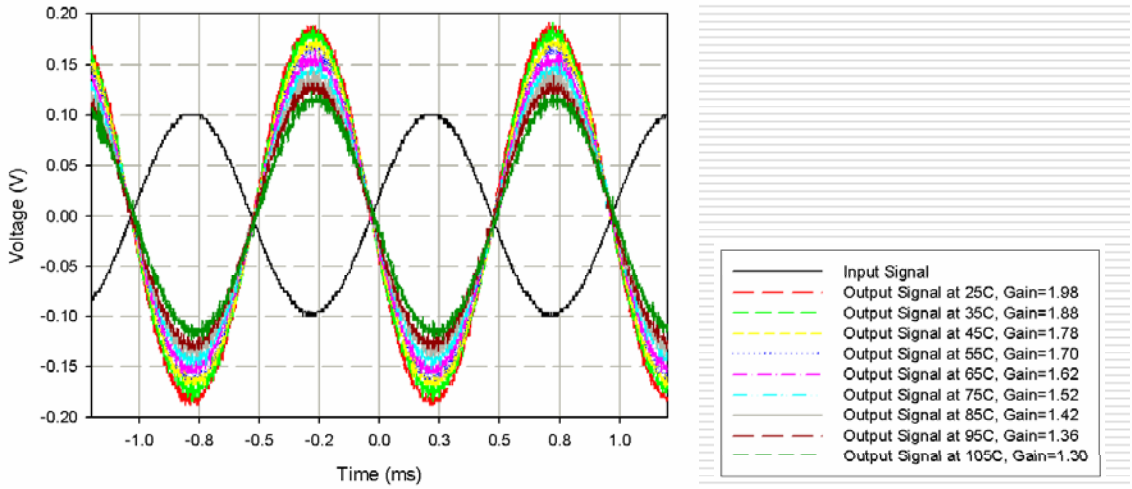
$$R(T) = R_0(1+\alpha(T-T_0))$$

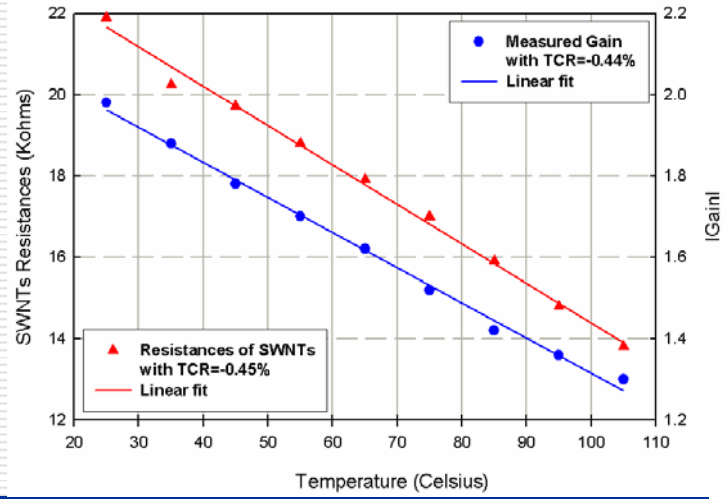
2D electrodes



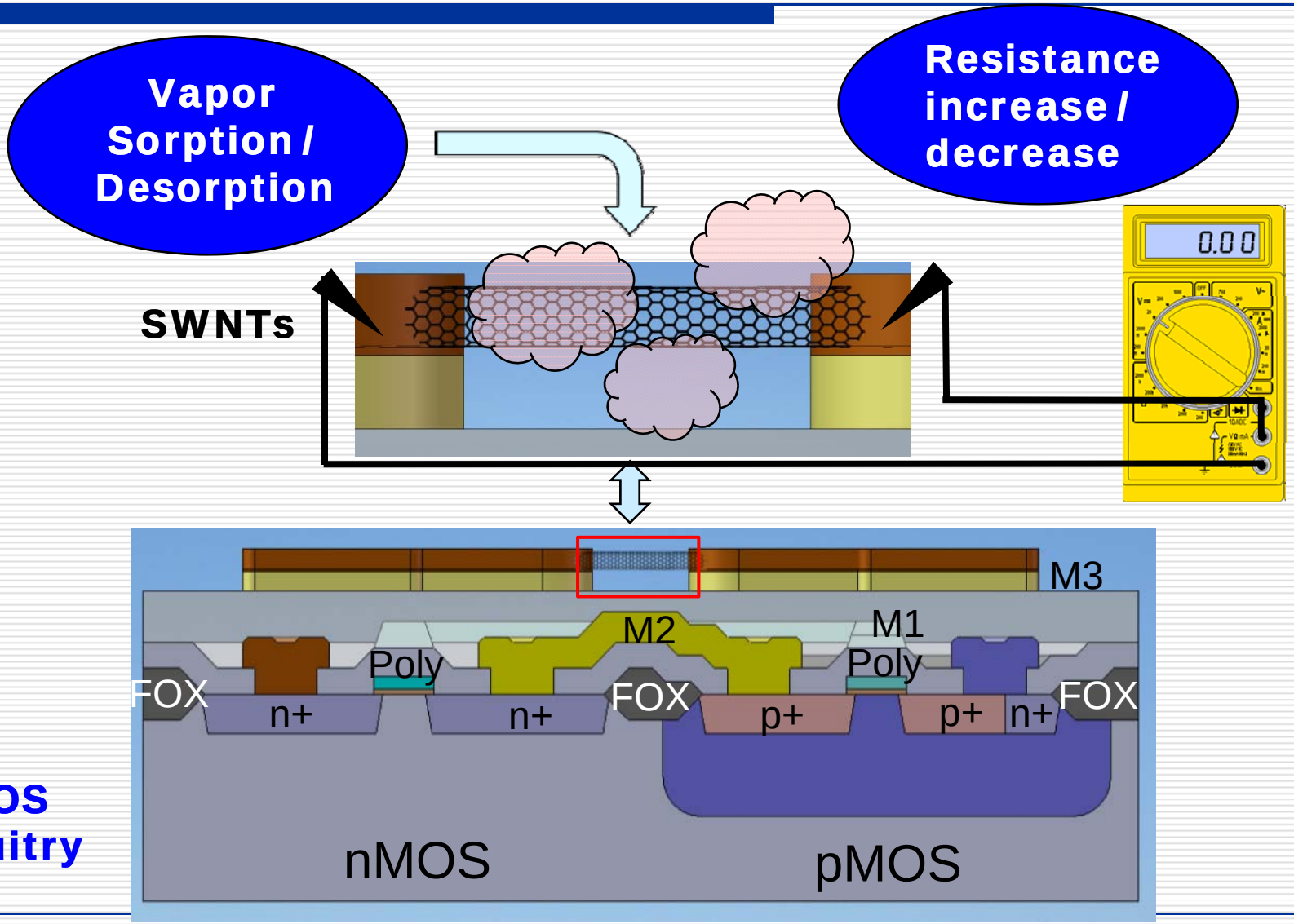


3D electrodes





Device Under Test



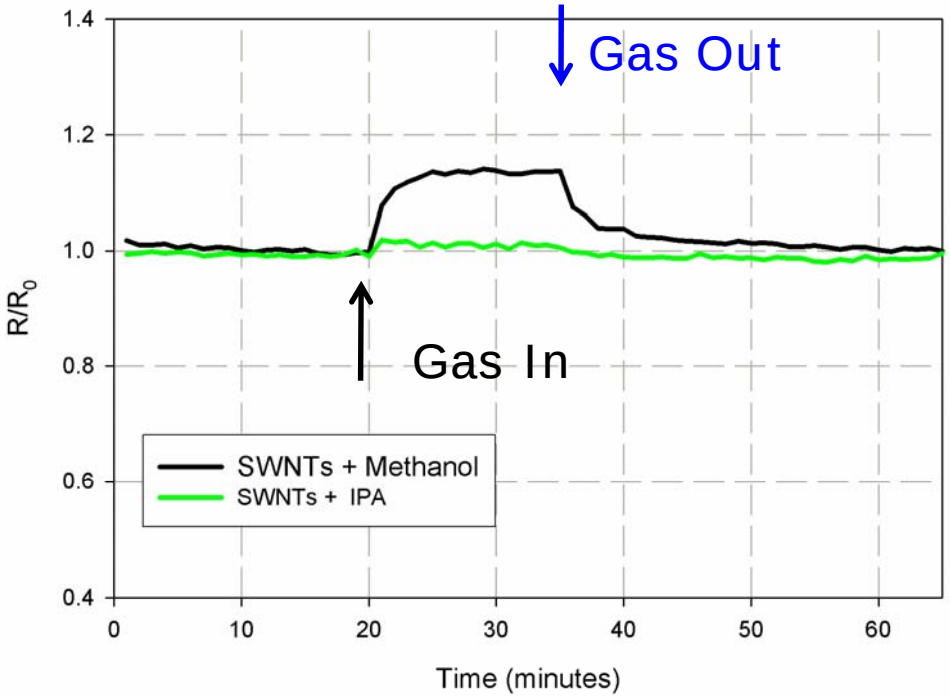
CMOS circuitry

Gas Sensing

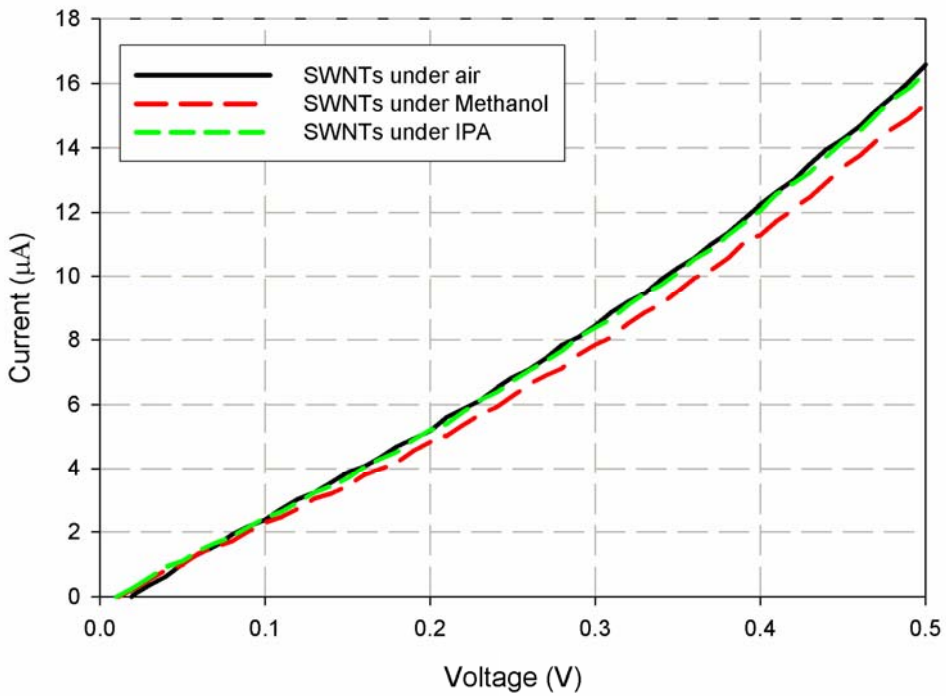
Saturation vapor concentration:

Methanol: ~97.48 torr @ 20°C

IPA: ~33 torr@ 20°C



Gas sensing properties of SWNTs. Resistance increased ~14.5% under methanol vapor and increased ~3.58% under IPA vapor



I-V measurements from the SWNT gas sensors

Conclusions

- Integration of SWNTs on to standard CMOS circuitry utilizing DEP assembly is demonstrated using a post CMOS process.
- The approach utilized post-CMOS processing which is low temperature, has high yield and is amenable to wafer scale manufacturing.
- An SWNT based thermal sensor has been realized on CMOS circuitry. The thermal response of the assembled CNTs obtained from two-terminal I-V measurements match the results obtained from the output gain of the op-amp.
- Gas sensing properties has been realized on CMOS circuitry for both Methanol and IPA vapor.
- This versatile approach can be extended for the integration of other nanostructures and nanomaterials onto CMOS electronics paving way for the realization of next generation of biological and chemical nanosensors and multifunctional nanosystems.

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