Heterogeneous Integration of Single-Walled Carbon Nanotubes with CMOS Circuitry

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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

Diagram showing:
- Nanowire Photovoltaic
- 3D CNT Gas Sensors
- Nanowire Energy Harvesting
- CMOS Circuitry
- 2D CNT Bio-Sensors
- RF Components
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

1) Mechanical Properties

<table>
<thead>
<tr>
<th></th>
<th>Young’s Modulus (GPa)</th>
<th>Tensile Strength (GPa)</th>
<th>Density (g/Cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWNT</td>
<td>1200</td>
<td>~150</td>
<td>2.6</td>
</tr>
<tr>
<td>SWNT</td>
<td>1054</td>
<td>75</td>
<td>1.3</td>
</tr>
<tr>
<td>SWNT bundle</td>
<td>563</td>
<td>~150</td>
<td>1.3</td>
</tr>
<tr>
<td>Graphite (in-plane)</td>
<td>350</td>
<td>2.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Steel</td>
<td>208</td>
<td>0.4</td>
<td>7.8</td>
</tr>
</tbody>
</table>

2) Electrical Properties

- Strongly depends on chirality of carbon nanotube
  - Ballistic electron transport
  - High current density ($10^9$ Amps/cm²) \( B.Q.\ Wei, \textit{Appl. Phys. Lett.} 2001 \)
  - Band gap for Semiconducting CNTs scale inversely with the diameter of the tube \( (E_g = 0.84 \text{ eV/d [nm]}) \) \( M, O’Connell, \textit{Carbon nanotubes}, 2006 \)
Applications of Carbon Nanotubes - Sensors -

Pressure Sensors:

Thermal Sensors:

BioSensors:

Gas Sensors:

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

Stampfer, Nano Letts., 2005

Besteman, Nano Letts., 2003

Stalii, Nano Letts., 2005
Nanoscale Assembly

Self Assembly

Tobias et al., Adv. Mater., 2005

Electrophoresis

DC

Drop Casting

Dip Coating

Brinker, J. Phys. III France, 1994

Dielectrophoresis

Neutral body

Positive DEP

Non-Uniform Field

Neutral body

Negative DEP

+V

- V
Dielectrophoretic (DEP) Assembly

Apply DC electric field:

\[ F = (m \cdot \nabla)E \]

Apply AC electric field:

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

Clausius-Mossotti factor:

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

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

For SWNTs

\[ K(\omega) = \begin{bmatrix} \varepsilon_p^* - \varepsilon_m^* \\ 3\varepsilon_m^* \end{bmatrix} \]

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

Positive and Negative DEP

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

\[ \varepsilon_p = 2.5 \varepsilon_0, \sigma_p = 10^5 \] and \[ \varepsilon_m = 78.36 \varepsilon_0, \]
\[ \sigma_m = 5.5 \times 10^{-6} \]
Electrode Design for Low Voltage DEP Assembly of Nanotubes

2D electrodes

3D electrodes

CNTs

nMOS

pMOS

2D electrodes

3D electrodes

n+ n+ p+ p+ p+n+

FOXPoly Poly

M1 M1 M1

M1

2D

3D

Single Finger

Multi Finger

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Chip Design (AMI 0.5 um CMOS technology)

2mm

Individual Op-amps

Op-amp

Assembly area

Stand alone 2D/3D electrodes

3D electrodes between M2&M3

2D electrodes between M3&M3

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Fabrication Process

2D CNT Assembly

Fabricated CMOS die

3D CNT Assembly

Photoresist Opening for RIE Etching

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

3D electrodes

Schematic of Operational Amplifier
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 25°C, Gain = 1.8
- Output Signal at 35°C, Gain = 1.8
- Output Signal at 45°C, Gain = 1.8
- Output Signal at 55°C, Gain = 1.8
- Output Signal at 65°C, Gain = 1.8
- Output Signal at 75°C, Gain = 1.8
- Output Signal at 85°C, Gain = 1.8
- Output Signal at 95°C, Gain = 1.8
- Output Signal at 105°C, Gain = 1.8

CMOS Temperature Response with External Resistances

- Voltage (V) vs. Time (ms)
Thermal Response of SWNTs integrated on CMOS Circuitry

2D electrodes

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

3D electrodes
Device Under Test

Vapor Sorption/Desorption

Resistance increase/decrease

SWNTs

CMOS circuitry

nMOS

pMOS

M1

M2

M3

n+ n+ p+ p+

Poly

Poly

n+ n+ p+ p+ n+

FOX

FOX

Poly

Poly

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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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