Carbon Nanotube Gas Sensing

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NSF Presentation
Carbon nanotube chemical sensors have the most positive short-term effects on the environment, national security, energy, and the economy.
Overview

• CNT applications
• Sensing applications
• Sensing requirements
• Standard sensors
• CNT sensors
• Science of CNT sensors
• Projected viability
• Future direction
## Short term outlook on carbon nanotube applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Feasibility</th>
<th>Environment</th>
<th>National security</th>
<th>Energy</th>
<th>Economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic devices</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Nonvolatile memory</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
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<tr>
<td>Nanotweezers</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
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<tr>
<td>Scanning probe</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
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<tr>
<td>Strong materials</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>Field emission displays</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>Hydrogen storage</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
<td>Gas Sensors</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>
Applications

- Environmental monitoring
- National security
- Medical Diagnostic Apparatus
- Space Exploration
- Domestic Gas Alarms
- Automotive applications
- Agricultural applications
Chemical Sensors

- Device that converts chemical quantity into electrical signal
  - Small, robust, and reliable construction
  - Selective and rapid response
  - Independence from environmental parameters
  - Reproducibility
  - Manufacturability using conventional microelectronic methods
  - Microelectronics compatibility

## Disadvantages of Existing Gas Sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Size</th>
<th>Power</th>
<th>Selectivity</th>
<th>Sensitivity</th>
<th>Stability</th>
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<tbody>
<tr>
<td>Analytical equipment</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Electrochemical sensors</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
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<tr>
<td>Catalytic bead sensors</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Metal Oxide Semiconductors</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>Conductive polymer sensors</td>
<td></td>
<td></td>
<td>X</td>
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</tbody>
</table>

X = unsatisfactory

http://www.sensorsmag.com/resources/businessdigest/sbd0704.shtm

Nanotubes in Sensing

- High Surface Area
- High Aspect Ratio
- Large Absorption Capacity
- Large change in electrical properties when in the presence of different gases at room temperature

www.ewels.info/img/science/nano.html
Gas Ionization Sensor

- Measures breakdown voltage to identify gas
  - Nanotubes lower breakdown voltage by 65%
- Gas quantities determined by current discharge
- Advantages:
  - Independent of Temp. and Humidity
  - No absorption (quick recovery)
- Disadvantages:
  - Not good at low concentrations (~25ppm when combined with gas chromatography)

FET- Based Sensor

- Measures drain current with given applied gate voltage
- Sensitivity on the order of ppm has been achieved
- Recovery time ~2 sec when gate voltage is removed
- Disadvantage: difficult to manufacture consistently


Chemoresistor

- Measures change in resistance
- CNTs form network on interdigitated electrodes (IDE)
- Enables electric contact between CNTs and electrodes over large areas
- Accessible for vapor adsorption to all CNTs
- Sensitivity:
  - < 44ppb for NO₂
- Recovery:
  - ~4sec

Chemicapacitor:

- Advantages
  - Stable
  - Highly sensitive (50 ppb)
  - Fast response time and recovery time (< 4 seconds)
  - Sensitive to wide range of chemical vapors (19 tested)
• MUCH cheaper than current solid-state sensors ($100 vs. $1500)

• Scalability limited only by lithography step

Physics of Chemicapacitor

- Enhanced electric field around nanotubes
- Net polarization of adsorbates
- Increase in relative capacitance, $\frac{\Delta C}{C}$
- Does not depend on chirality or diameter of NT

• Binding of analytes to nanotubes is governed by Van der Waals interactions
  → Broad range of compounds can be detected
Enhancing Selectivity

Functionalize nanotubes

Hydrogen bonding acidic polysilane/allyltrichlorosilane

Functionalization using polymers filters out common interference from vapors

DMMP, stimulant for nerve agent sarin, preferentially binds to polymer-coated nanotubes

### Feasibility

<table>
<thead>
<tr>
<th>Selectivity</th>
<th>Sensitivity</th>
<th>Response Time</th>
<th>Cost (per unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Combustible Gas</strong></td>
<td>Any combustibles</td>
<td>1000 ppm</td>
<td>$200</td>
</tr>
<tr>
<td><strong>Metallic Oxide Semiconductor</strong></td>
<td>None</td>
<td>200 ppm</td>
<td>$3000</td>
</tr>
<tr>
<td><strong>Polymer Chemicapacitor</strong></td>
<td>Medium</td>
<td>2 ppm</td>
<td>$10,000</td>
</tr>
<tr>
<td><strong>SWNT</strong></td>
<td>High</td>
<td>10,000 ppm - sub ppb</td>
<td>$150</td>
</tr>
</tbody>
</table>

http://www.cdnsafety.com/articles/selecting_gas_detectors.htm
Commercialization

- **Integrated Nanosystem, Inc.**
  - Low power (<1 mW)
  - Small (1 cm²)
  - Sensitive (ppt-ppm)
  - Multiplexing capability

- **Nanomix**
  - H₂ leak detection sensors
    - Only responds to H₂
    - $150/unit. Possibly $50/unit in future.
    - Wireless capabilities

http://www.sensorsmag.com/resources/businessdigest/sbd0704.shtml
Interview with sales representative at KWJ Engineering (510.794.4296) who is Nanomix’s distributor.
Moving forward

• Implications are wide ranging
  – Homeland security, economy, environment, etc.
• Background science exists
  – Solid state gas sensors
  – Research on CNT-based gas sensors proves potential to be better than current sensors
• Commercializable
  – INI and Nanomix
• Barriers remain
  – Selectivity, sensitivity, response time