Carbon Nanotube Electronics

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## Carbon Nanotubes – Superior Electronic Properties

<table>
<thead>
<tr>
<th>3D – graphite</th>
<th>2D – graphene</th>
<th>1D – Carbon nanotube</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Graphite" /></td>
<td><img src="image" alt="Graphene" /></td>
<td><img src="image" alt="Carbon nanotube" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>GaAs</th>
<th>InGaAs*</th>
<th>GaN</th>
<th>CNT</th>
<th>Graphene</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_G), eV</td>
<td>1.1</td>
<td>1.4</td>
<td>0.7</td>
<td>3.4</td>
<td>0.4 - 1</td>
<td>0</td>
</tr>
<tr>
<td>(E_{BR}), (10^5) V/cm</td>
<td>5.7</td>
<td>6.4</td>
<td>4</td>
<td>40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(\mu_0), cm(^2)/Vs</td>
<td>710</td>
<td>4700</td>
<td>7000</td>
<td>680</td>
<td>(&gt;10,000)</td>
<td>(&gt;10,000)</td>
</tr>
<tr>
<td>(v_{peak}), (10^7)cm/s</td>
<td>1</td>
<td>2</td>
<td>2.5-3</td>
<td>2.5</td>
<td>2 - 4</td>
<td>2 - 4</td>
</tr>
<tr>
<td>(v_{sat}), (10^7)cm/s</td>
<td>1</td>
<td>0.8</td>
<td>0.7</td>
<td>1.5-2</td>
<td>2 - 4</td>
<td>2 - 4</td>
</tr>
<tr>
<td>(\kappa), W/cm-K</td>
<td>1.3</td>
<td>0.5</td>
<td>0.05</td>
<td>1.2**</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- **Very high carrier mobility** (\(>10,000\) cm\(^2\)/Vs at room temperature) for high speed transistor
- **High carrier velocity**: saturation velocity \(\sim 4 \times 10^7\) cm/s
**Digital Electronics**

**Research Options:**
- High-K & Metal Gate
- Non-planar Trigate
- III-V, CNT, NW

**Problem:**
Coexistence of metallic and semiconducting nanotubes

**Goal:**
Remove metallic nanotubes

**My innovation:**
Selective synthesis of predominant semiconducting nanotubes
Radio frequency Electronics

My innovation:
High performance carbon nanotube RF transistors and circuits

Key factors in RF:
- Mobility
- Conductivity
- Linearity
Synthesis of Predominantly Semiconducting Nanotubes

Use of isopropanol (IPA) as the carbon source

- 9 feet-long growth furnace with three-zone

Gas in

Quartz with patterned catalyst

Gas out

- High concentration of H₂O suppress of metallic CNT growth

Switch off

Semiconducting CNT purity:
IPA: ~97% (best device);
Ethanol: 52%

Application: Thin-film Electronics

- on/off = $10^4$
- Mobility = 116 cm$^2$/V·s

Thin film Macroelectronics (AMOLED)

Thin film Macroelectronics

Device SEM

Drain Current ($\mu$A) vs. Drain Voltage (V)

Drain Current ($\mu$A) vs. Gate Voltage (V)

Gate Voltage (V) from -10 to 10 V in 2 V step

OLED

20 x 25 pixel array

Radio Frequency (RF) electronics

**Previous design**

- Misalignment
- Parasitic capacitance
- Low yield


**New design (T-gate)**

- Self-aligned technology
- Reduce fringe capacitance
- Reduce gate resistance
- High yield

Carbon nanotube RF transistor

- Wafer scale nanotube deposition

Cut-off frequency of 88 GHz and maximum Power Gain frequency of 37 GHz are achieved.

**Frequency doubler:** Offer a new degree of freedom in designing frequency multiplier chains.

**Mixer:** Shift a signal from one frequency to another, keeping the properties of the initial signal.

**Power (dBm)**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>RF</th>
<th>LO</th>
<th>LO+RF</th>
<th>2LO</th>
<th>2RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>-12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>-14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>-16</td>
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<td></td>
</tr>
<tr>
<td>2.0</td>
<td>-18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>-20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.8</td>
<td>-22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Conversion gain:** 

-24.5 dB

**RF:** 1 GHz  
**LO:** 1.2 GHz  
**IF:** 0.2 GHz

Future plan: Hybrid circuit

Small signal model

Low noise amplifier

CNTFET integrated with matching network
THANK YOU!

http://nanolab.usc.edu/