NEM Relays Using 2-Dimensional Nanomaterials for Low Energy Contacts

Seunghyun Lee, Ji Cao

10/29/2013

Professor H. -S. Philip Wong
Electrical Engineering,
Stanford University
Van der Waals materials – Nanomechanical Relays

1. Graphene
2. Transition Metal Dichalcogenides
3. Rolled-up graphene: carbon nanotubes

Nanoscale interfaces formed by different atomic bonds, band structures, and dimensions

Nat. Nanotechnol. 6,147–150 (2011)
Graphene Beam Relays

**Schematic Device Cross-Section**

- Graphene
- SiO₂
- Graphene beam
- Cr/Au
- Ni
- 50-100nm

**SEM**

- Graphene beam
- S
- G
- Ni
- Si
- SiO₂

**I-V**

- Beam current (A) vs. Beam voltage (V)
- Pull-in observed

- Beam voltage (V): 10⁻¹⁴ to 10⁻²
- Beam current (A): 10⁻¹² to 10⁻¹⁴
# Graphene for low Energy Contact

Graphene as a mechanical contact material in the nanoscale domain

| Surface Properties | • Weak vdW interaction. Low surface energy [3]   
|                    | • Low Hamaker’s constant (order of 1e-20 J [4]) |
| Thermal Properties | • Thermally resistant [1] (will prevent microwelding which causes permanent stiction.)   
|                    | • Graphene doesn’t burn or react easily at high temperature. [1]   
|                    | • A good thermal conductor [1]   |
| Electrical Properties | • Conductive. Zero bandgap material [1]   
|                          | • Graphene can withstand record current density [1]   |
| Mechanical Properties | • In nanoscale, the highest mechanical strength. Strong C-C covalent bonds. [1] |
| Chemical Properties | • Act as surface passivation to reduce metal oxidation. (Graphene is a barrier for oxygen.[7])   
|                          | • Resistant to humidity (metal is affected by humidity. For graphene, the water molecules just act as dopants.) |
| Practicality | • Low cost: much more common than hard rare earth materials(Ru, Ir) used in MEMS relay   
|                          | • Large area synthesis possible with chemical vapor deposition [1]   
|                          | • Can be transferred to arbitrary substrate [1]   |

References:

Graphene for low Energy Contact

Dupre adhesion energy $W_a = \gamma_1 + \gamma_2 + \gamma_{12}$

Surface energy: $\gamma_1, \gamma_2$
Interface energy: $\gamma_{12}$

Table 2. Work of Adhesion between Solid–Liquid Interfaces

<table>
<thead>
<tr>
<th>materials</th>
<th>water (mJ/m²)</th>
<th>formamide (mJ/m²)</th>
<th>diiodo-methane (mJ/m²)</th>
<th>ethylene glycol (mJ/m²)</th>
<th>glycerol (mJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>graphite</td>
<td>62.6</td>
<td>99.4</td>
<td>97.9</td>
<td>75.4</td>
<td>89.8</td>
</tr>
<tr>
<td>graphene oxide</td>
<td>104.2</td>
<td>114.1</td>
<td>90.4</td>
<td>90.8</td>
<td>107.9</td>
</tr>
<tr>
<td>graphene</td>
<td>29.0</td>
<td>69.1</td>
<td>88.4</td>
<td>59.3</td>
<td>41.4</td>
</tr>
</tbody>
</table>

S. Wang et al., Langmuir 25, 11078-11081 (2009)
How about MoS$_2$?

A different van der Waals material

- Monolayer TMDs are the thinnest material known that have bandgaps.

*Unlike graphene*, atomically thin TMDs have
- High on/off ratio (~$10^8$) [3]
- Low off-state conductance
- Direct bandgap (1.8 eV)
- Strong current saturation behavior
- Extreme thinness opens up several integration options with current CMOS process.
- Potential for unconventional electronics on exotic platforms (i.e. stretchable, flexible substrates.) [5]

Large Area MoS$_2$ synthesis

Synthesis Infrastructure

- Sulfur boat
- Inner tube for controlled gas flow
- MoO$_3$ and substrate
- Baffles to trap sulfur gas
- Furnace Temperature Profile
Deposited MoO3 or non-uniform films

Raman Spectroscopy

Auger Spectroscopy

Surfurs

Mo

Oxygen

Sensitive to temperature, pressure, flow rate, source ratio, growth time
Large Area TMD synthesis

Uniform Single Layer MoS$_2$ film synthesized up to 1 cm x 1 cm

Confirmed Raman signal on 10 random locations with $E^{1\,2g}$ $A^{1\,g}$ peak frequency difference of 18-19 cm$^{-1}$
Graphene Nanomechanical Relays

- The actuator design is a concentric drum structure.
- Varying area and actuating diaphragm size.
- Additional body terminal for more control of the pull-in voltage.
- Experimentally investigate the relationship between the adhesive force, the hysteresis, the contact materials, and the contact area.
Optimization of graphene (single and multilayer) transfer on various substrates

Only van der Waals interaction between the substrate and graphene.
Carbon Nanotube NEM Relays - Fabrication Technique

CNT is a rolled-up graphene.

• Yield: > 85%;
• Error: Sub-50 nm;
• Lateral deviation: < 2.5%;
• Adjustable density

Typical Demonstrations of CNT NEM Switches

J. Cao, et al., MEMS 2012.
6-Terminal CNT clamped-clamped NEM switches with low pull-in voltage.
Summary

1. Demonstrated graphene beam relay
2. Layered vdW materials for interfaces in nanomechanical relays
3. CVD Synthesis of large area MoS2
4. Design of concentric drum relays for experimental verification
5. Graphene transfer
6. Status of carbon nanotube relays
Acknowledgments

The authors would like to thank:

- E3S : Center for Energy Efficient Electronics Science
- The Swiss Nanotera project CABTURES (SNF Number: 20NAN0_123614);
- The FP6 IST-028158 project NANORF (Hybrid Carbon Nanotube – CMOS RF Microsystems);
- Swiss National Science Foundation