Single Crystal Diamond NEMS Switch

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普段の生活のエネルギー消費を減らす必要！

ナノマシンスイッチ: 省エネルギー技術（ゼロ）として期待。
## MEMS switch: Merits

### Advantages over semiconductor devices

<table>
<thead>
<tr>
<th>Property</th>
<th>MEMS switch</th>
<th>Semiconductor switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage</td>
<td>zero</td>
<td>Large</td>
</tr>
<tr>
<td>Power loss</td>
<td>~0</td>
<td>&gt;1 uW</td>
</tr>
<tr>
<td>Speed</td>
<td>Slow (10µs)</td>
<td>Fast (10ns)</td>
</tr>
<tr>
<td>Insertion loss</td>
<td>Small (&lt;0.2dB)</td>
<td>Large (&gt;1dB)</td>
</tr>
<tr>
<td>Isolation</td>
<td>Good (&gt;30dB)</td>
<td>Poor (&lt;25dB)</td>
</tr>
<tr>
<td>Linearity</td>
<td>Excellent</td>
<td>Poor</td>
</tr>
<tr>
<td>High and low temperatures</td>
<td>Excellent</td>
<td>Poor</td>
</tr>
</tbody>
</table>

### But, poor reliability due to

(i) Surface stiction
(ii) Mechanical abrasion

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Semiconductor devices consume power in OFF state!
Diamond MEMS: route toward high reliability and high performance

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>SWCNT</th>
<th>Graphene</th>
<th>Si</th>
<th>SiC</th>
<th>AlN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>3.52</td>
<td>1.3-1.4</td>
<td>&gt;1</td>
<td>2.33</td>
<td>3.21</td>
<td>3.3</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>1200</td>
<td>~1000</td>
<td>~1000</td>
<td>130</td>
<td>450</td>
<td>100-400</td>
</tr>
<tr>
<td>Hardness (GPa)</td>
<td>100</td>
<td>—</td>
<td>—</td>
<td>10</td>
<td>33</td>
<td>11.8</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>~0.05</td>
<td>0.01-2</td>
<td>0.07-0.5</td>
<td>0.4-0.6</td>
<td>0.2-0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Strength (GPa)</td>
<td>5.3</td>
<td>13-55</td>
<td>130</td>
<td>1.0</td>
<td>5.2</td>
<td>0.25</td>
</tr>
<tr>
<td>Thermal conductivity(Wcm⁻¹K⁻¹)</td>
<td>24</td>
<td>35</td>
<td>10-53</td>
<td>1.5</td>
<td>5</td>
<td>1.75</td>
</tr>
<tr>
<td>Bandgap (eV)</td>
<td>5.5</td>
<td>0-2</td>
<td>~0</td>
<td>1.1</td>
<td>3.3</td>
<td>6.2</td>
</tr>
<tr>
<td>Electron mobility (cm²V⁻¹s⁻¹)</td>
<td>4500</td>
<td>100,000</td>
<td>200,000</td>
<td>1450</td>
<td>900</td>
<td>426</td>
</tr>
<tr>
<td>Hole mobility(cm²s⁻¹)</td>
<td>3800</td>
<td>4,000</td>
<td>&gt;100,000</td>
<td>480</td>
<td>120</td>
<td>14</td>
</tr>
<tr>
<td>Breakdown field (MVcm⁻¹)</td>
<td>10</td>
<td>—</td>
<td>—</td>
<td>0.3</td>
<td>3.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>5.5</td>
<td>—</td>
<td>—</td>
<td>11.8</td>
<td>9.7</td>
<td>8.9</td>
</tr>
</tbody>
</table>

Current MEMS: intrinsic limitations!!

The highest Young’s modulus
The lowest friction coefficient
Hydrophobic surface
Highest thermal conductivity
Tunable electrical conductivity
The best material

Merits
Challenges and Strategies in Diamond MEMS

What process....? What device concept......?

Difficulties
- Batch fabrication of single crystal diamond MEMS structures.
- Lack of device concepts compatible with the fabrication process.

Aims
- Establish unique process for diamond MEMS structures.
- Develop high-performance diamond MEMS/NEMS devices.
- Create novel device concepts.

Strategies
- No direct deposition of diamond on sacrificial layers.
- Diamond-on-Diamond lateral device concept.
Diamond growth

MPCVD

Parameters:
Gas: $H_2$ (500 sccm), $CH_4$ (0.4 sccm)
RF Power: 400 W
Pressure: 80 Torr
Sub. Tem: 900-950°C
[B]:1000 ppm $10^{20}$cm$^{-3}$
Substrate: Ib (100)---100 ppm nitrogen
Thickness: 0.1-0.5µm
Batch production of micro-scale M/NEMS structures


Quality of the MEMS/NEMS structure

- Diamond
- Graphite
- Diamond

Intensity (a.u.) vs. Wavenumber (cm$^{-1}$)

Counts (a.u.) vs. Energy loss (eV)

Protection Pt layer

Boron doped diamond

Energy loss (eV) vs. Wavelength (nm)

- Relaxed free-standing diamond beam
- Epilayer on implanted region with graphite beneath
- Diamond substrate

Intensity (a.u.) vs. Wavenumber (cm$^{-1}$)
Nanoindentation of MEMS structures

Young’s modulus: 800 ± 200 GPa (Calibrated by Si cantilever)

Nanoelectromechanical switch: 2-terminal
Nanoelectromechanical switch: 3-terminal

Drain current (A) vs. Gate voltage (V)

ON-state

OFF-state

Drain current (A) vs. Gate Voltage (V)

Current (A) vs. Time (s)
3-T NEMS switch: Reliability

$V_G$ OFF-state

$10^5$ switching cycles

100Hz AC $V_G$

High temperature operation

150 °C
200 °C
250 °C
Modeling and simulation of NEMS switch

\[-\nabla \cdot (\varepsilon \nabla V) = 0\]

Potential in the air around the beam

\[F_{es} = -\frac{1}{2} (E \cdot D) n + (n \cdot E) D^T\]

\[F_{es}: \text{Electrostatic force density of the beam}\]
\[E: \text{electric field, } D: \text{displacement vector}\]

Pull-in voltage: defined as the beam contact to the gate.
\[V_{\text{pull-in}} = \sqrt{\frac{4c_1B}{\varepsilon_0 L^4 c_2^2 (1 + c_3 \frac{g}{W})}}\]

\[L: \text{length, } W: \text{width, } t: \text{thickness}\]

\[B = E_0 t^3 g^3\]
Modeling and simulation of NEMS switch
Comparison between experiment and simulation:

- High Young's Modulus
- Good reproducibility
- Consistence between experiment and simulation

Young's modulus = 1100 GPa

Joint stress much lower than fracture strength
- Drain voltage affecting pull-in voltage
Applications of diamond M/NEMS Switch: H⁴

High power
High temperature
High frequency
High reliability

Nano-Macro Machines Switch

携帯電話や無線LANなどの無線通信
(待機ゼロ)電源制御装置
耐環境デバイス:高温論理回路
メモリ
Summary

For the first time

- Single-crystal diamond NEMS switch was fabricated.
- Batch production of SCD MEMS/NEMS structures were developed.

- The diamond NEMS switches exhibit high performance.
  1. High controllability.
  2. High reproducibility.
  3. Good reliability.

- Modeling and simulation were made and were consistent with experiments