Impact of Carbon Material on RF MEMS Switch


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Abstract: Carbon materials such as Graphene and carbon nano tube promise a new generation of RF MEMS devices that bring many advantages due to their very high performances such as low mass, high Young's modulus and electrical conductivity. In this paper, the properties of Graphene for RF M/NEMS applications are briefly described. We compare the mechanical behaviour of Graphene switches with metallic RF MEMS switches such as Aluminium and Gold. The analytical study and simulation results show that the actuation voltage of Al and Au switches is high (35 V) whereas the actuation voltage for the Graphene switch is low (7.7 V). Also, the switching time of Graphene switch is 3.5 ns while the switching time for metallic switches is approximately 17µs.

Keywords: Graphene, RF MEMS, NEMS, actuation voltage, switching time.

1. Introduction

Complementary metal–oxide–semiconductor (CMOS) is a major class of integrated circuits with significant progress during the past four decades. According to International Technology Roadmap for Semiconductors (ITRS), by using top-down approach the physical gate length of CMOS will be smaller than 16 nm in 2016. Micro/nano electro mechanical system (MEMS/NEMS), which shows the distinguished feature of multifunction (sensing, communication, and actuation), is a rapidly growing field building on the existing Si processing infrastructure [1-4].

MEMS technology has already had a significant impact on medical, automobile, aerospace and information technology areas [3, 5]. NEMS, which is about a thousand times smaller than MEMS, has the potential to make a revolutionary technology for these areas. MEMS/NEMS switches are highly attractive in radio-frequency (RF) microwave millimetre wave systems, logic circuit, and memory due to their high performance. Advances in micro/nanoelectromechanical devices and systems (MEMS/NEMS) in recent decades suggest the possibility of revisiting mechanical logic.

MEMS/NEMS switch exhibits low-insertion loss, good isolation, and excellent linearity much better than semiconductor devices for high frequency (GHz) RF applications [3, 6, 7]. Carbon allotropes such as graphene and carbon nano tubes have shown superior electrical and mechanical performance compared to other types of materials. Due to the great advantage of these materials, they can be very good candidates for development of the RF M/NEMS switches [8].

Graphene, a one-atom-thick layer of carbon that resembles a flat sheet of chicken wire at nanoscale, has the potential to revolutionize electronics because the electricity conductivity much better than the gold and copper wires used in current devices. Moreover, it has a hexagonal structure where each atom forming 3 bonds with each of its nearest neighbours (Fig. 1). These are known as the σ bonds oriented towards these neighboring atoms and formed from 3 of the valence electrons. These covalent carbon-carbon bonds are nearly equivalent to the bonds holding diamond together giving graphene similar mechanical and thermal properties as diamond. The fourth valence electron does not participate in covalent bonding. It is in the 2pz state oriented perpendicular to the sheet of graphite and forms a conducting π band. The remarkable electronic properties of carbon nanotubes are a direct consequence of the peculiar band structure of graphene, a zero bandgap semiconductor with 2 linearly dispersing bands that touch at the corners of the first Brillouin zone [9]. Bulk graphite has been studied for decades [10]. But until recently there were no experiments on graphene. This was due to the difficulty in separating and isolating single layers of graphene for study.

There are two types of bonds in atomic structure: Firstly, the C-C covalent (σ) bonds which is the strong covalent bonds and responsible for the mechanical properties. Secondly, the π bonds which is due to the van der Waals force and is used to describe the electronic properties of graphene [1].

2. Electrical and mechanical properties of graphene

The microwave and electronic properties of graphene is investigated in [1, 3, 4, 6]. The discovery of graphene revolutionizes the traditional view that 2D crystal is not stable in freestanding state.
One prominent feature of graphene is its zero-bandgap with massless charge carriers, which are ruled by Dirac equation [7, 11, 12]. Due to its special electronic band structure, graphene possess exotic properties such as ultra-high room-temperature carrier mobilities (>15,000 cm²V⁻¹s⁻¹) even for a high carrier density (>10¹² cm⁻²), a high thermal conductivity, ultrahigh stiffness and strength, and hydrophobic surface [3, 7, 13]. The electrical conductivity for doped graphene is quite high, at room temperature it may even be higher than that of copper.

These properties allow graphene a potential candidate for NEMS. The Young’s modulus of the graphene sheets was varied from 250–1000 GPa. The electrical properties of graphene depend on the preparation methods. The electrical resistivity of graphene sheet was in the order of 10⁻³ Ωm, less than the resistivity of silver [14-16].

TABLE I: Electrical and mechanical properties of material

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity (Ω.m)</th>
<th>Mechanical resonance frequency (Hz)</th>
<th>Young’s modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphene</td>
<td>10⁻³</td>
<td>≈178×10⁶</td>
<td>1000</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2.82×10⁻³</td>
<td>≈106×10⁷</td>
<td>70</td>
</tr>
<tr>
<td>Gold</td>
<td>2.21×10⁻³</td>
<td>≈39.5×10⁷</td>
<td>79</td>
</tr>
</tbody>
</table>

3. NEMS Switches based on Graphene

Carbon-based nanomaterials, including nanowires and carbon nanotubes, have been employed in NEMS devices with much success [17-20]. Graphene is expected to be an excellent candidate for NEMS devices owing to its different properties [8, 21-24]. The fabrication process of RF NEMS switches based on graphene is different to that of conventional RF MEMS switches and is more sophisticated than that used for conventional MEMS switches. Furthermore, graphene-based devices have advantages in scaled-up device fabrication due to the recent progress in large area graphene growth and lithographic patterning of graphene nanostripes [25-29]. Recently, NEMS switches (Fig. 2) based on suspended graphene have been fabricated and explored, but little success has been achieved in terms of repeatable switching [30, 31].

The RF parameters of the switch strongly depend on the amount of capacitance in the up and down states. The size reduction has a negative impact on RF parameters.

This problem is resolved by matching techniques. Generally, the RF parameters of NEMS switches are not good for the microwave frequency but this may change in the future.

4. Calculation of Pull-in Voltage for Graphene Beams

An analytical expression for the pull-in voltage of MEMS switches has been published in [32]. When the applied potential difference between the beam and the ground plane exceeds a certain potential, the movable structure becomes unstable and collapses onto the ground plane. Pull-in voltage or the collapse voltage is the potential which causes the graphene sheet to collapse onto the ground plane.

When the pull-in voltage is applied, the flexible structure comes in contact with the ground plane, and the device is said to be in the ON state. When the potential is released, the flexible structure and the ground plane are separated, in this case the device is said to be in the OFF state. The spring constant of a fixed- fixed beam with a distributed load is

\[ k = \frac{32Ew}{l} \left( \frac{t}{l} \right)^3 \]

(1)

Where E is the Young’s modulus, w is the width, t is the thickness and l is the length of the beam. Spring constant value computed using Equation (1). With a one-dimensional lumped model, the expression for pull-in voltage is given by [3, 11].

\[ V_{pull-in} = \sqrt{\frac{8\varepsilon_0\epsilon_0 g_0^3}{27\varepsilon_0 w l}} \]

(2)

Where \( g_0 \) is the air gap between beam and transmission line, and \( \varepsilon_0 \) is the vacuum permittivity (8.854×10⁻¹² F/m). Equation (2) is identical to the pull-in voltage expression derived in [3] for MEMS. It is obvious that the size of RF NEMS switches is smaller than the MEMS switches. Lowering the spring constant does not affect the size of switches. However, methods for lowering the actuation voltage by decreasing the gap increase the size of MEMS switches. This is due to the micro structures that they use for reducing the actuation voltage. By properly designing the geometric parameters,
i.e., NEMS switch, one can achieve low driving voltage by using electrostatic actuation [3, 4, 6, 11, 16]. Characteristics of the MEMS Beam (aluminium and gold) and NEMS graphene beam shown in TABLE II and both of them are of the fixed–fixed type. Pull-in voltage for aluminium and gold MEMS switch and NEMS graphene beam switch are calculated by using Equation (2) shown in Fig. 3. According to TABLE I and Fig. 3, as the young’s modulus increases the pull-in voltage decreases.

TABLE II: Characteristics of the MEMS and NEMS Beam [12, 32]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Aluminium and Gold</th>
<th>Graphene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>l</td>
<td>300 µm</td>
<td>0.7 µm</td>
</tr>
<tr>
<td>Thickness</td>
<td>t</td>
<td>0.3 µm</td>
<td>2.3 nm</td>
</tr>
<tr>
<td>Pull-down electrode length</td>
<td>W</td>
<td>80 µm</td>
<td>0.7 µm</td>
</tr>
<tr>
<td>Beam width</td>
<td>w</td>
<td>120 µm</td>
<td>1 µm</td>
</tr>
<tr>
<td>Gap height</td>
<td>g₀</td>
<td>2.5 µm</td>
<td>0.1 µm</td>
</tr>
<tr>
<td>Spring constant</td>
<td>κ</td>
<td>22.5 N/m</td>
<td>1.25 N/m</td>
</tr>
<tr>
<td>Mass</td>
<td>m</td>
<td>5.1×10⁻¹¹ kg(Al)</td>
<td>10⁻¹⁸ kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.6×10⁻¹⁰ kg(Au)</td>
<td></td>
</tr>
</tbody>
</table>

Where x is the bridge displacement, m is the bridge mass, A is the actuation area, and V is the applied voltage. Natural frequency equation (ω = √(k/m)) is used to calculate the bridge mass. Equation (3) is non-linear differential equation and its solution can be obtained using a non-linear solver such as Mathematica. The boundary conditions are as t=0: x=0, dx/dt=0 and the above equation is valid until the contact is achieved.

Figure 4 present the time-domain response for the MEMS/NEMS switch under applied voltage. As mentioned, in MEMS switch the gap between the membrane and the dielectric is about 2.5 μm. Whereas the gap is about 0.1 μm for graphene NEMS switch. The switching time for aluminium, gold, and graphene beam are approximately 6.56 µs, 17.4 µs, and 3.54 ns respectively. As can be seen the switching time is decreased by designing small size devices.

5. Switching Time Calculation Using the Equation of Motion

Switching time is the nonlinear dynamic analysis and mathematical modeling has been used to describe the switch dynamics. The displacement of switch’s beam shown in Figure 2 is governed by the simplified equation of motion [3].

\[ m \frac{d^2x}{dt^2} + kx = \frac{1}{2} \varepsilon_0 A V^2 \left( \frac{2}{g_0 - x} \right)^2 \]  \hspace{1cm} (2)

Fig. 4: Switching time for: (a) Aluminium and gold beam (b) Graphene beam

6. Conclusion

Special efforts on the mechanical behaviour were made in MEMS/NEMS switches based on beam materials. This paper shows that graphene possessed a number of excellent properties for NEMS applications. NEMS switches made from these graphene are expected to exhibit high-speed switching and high reliability and avoid stiction and abrasion often occurred in similar Si-based devices. TABLE III lists the pull-in voltage and
switching time for different beam materials. Electrostatically, the Al and Au beam devices had to be actuated at high voltage whereas; the actuation voltage for the graphene beam is low and suitable for low voltage application such as wireless communication systems. Also, the switching time due to the excellent properties of graphene significantly reduced. Despite great progress, carbon-based MEMS/NEMS is still a young field.

Acknowledgements

The authors would like to express their sincere thanks to Mrs Narjess Ansari for his valuable comments.

TABLE III: Performance comparison of different beam material

<table>
<thead>
<tr>
<th>Beam material</th>
<th>Pull-in voltage (V)</th>
<th>Switching time (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>35</td>
<td>6.56 x 10^-6</td>
</tr>
<tr>
<td>Gold</td>
<td>7.7</td>
<td>17.4 x 10^-9</td>
</tr>
<tr>
<td>Graphene</td>
<td>7.7</td>
<td>3.54 x 10^-9</td>
</tr>
</tbody>
</table>

References