Analytical and Numerical Modeling of Graphene based RF-NEMS Switch

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Abstract. We report the analytical and simulation of graphene based RF-NEMS switch to get the lowest actuation voltage and better RF-performance. Fix-fix type graphene based switch is actuated electrostatically. We have varied the design parameters such as length, width and thickness to get desired output such as low actuation voltage, better isolation and less insertion loss. The conductivity of graphene membrane is carried out in up and down-state position of the switch. Modal analysis is done and Scattering parameters are obtained using HFSS (High frequency structural simulation). Our result shows low pull in voltage that is less than 2 volt, better isolation of -54 dB and less insertion loss is reported for particular dimension. It is concluded that graphene can be best material for RF-NEMS switch. These results encourage taking further research for fabrication and characterization of RF-NEMS switch.

Keywords: Graphene, Pull in voltage, Insertion loss, Isolation, RF-NEMS.

1. Introduction

2D materials can be categorized as 2D allotropes of various elements or compounds (usually consisting of two covalent bond elements). Graphene is in a class of 2D material which is obtained by graphite. Chemically graphene is most reactive form of carbon atom only form of carbon atom (and generally all solid materials) in which each single atom is in exposure for chemical reaction from two sides (due to the 2D structure). Two scientists named Geim and Novoselov shifted single layer graphene from graphite on a silicon wafer using a technique named scotch-tape [1]. Due to this work they got nobel prize in physics in 2010.

Graphene is a carbon monolayer set in a honeycomb frame having carbon bond length of 0.142 nm, thinnest material and attracted researcher due to its properties. It is having young’s modulus up to 1 TPa, thermal conductivity 5000 W / mK) [2] excellent ductility stretchable up to 20% [3, 4]. It is stronger than steel, pliable, transparent, and conductive of both heat and electricity. Due to this graphene has attracted researcher for graphene based RF-NEMS switches. [5-9]

Graphene based nano electromechanical system (NEMS) could replace semiconductor switches due to its properties such as high isolation at high frequency, zero dc off current, low actuation voltage as well as fast switching. The drawbacks of MOS switches) such as ability to work at only low frequency as well as large amount of power dissipation is overcome by graphene based RF-NEMS switches. Thus graphene based RF-NEMS switch can have superb performance than those conventional switches. Electrostatic actuation makes graphene based switches more superb as electrostatic actuation causes low leakage current as well as high ON-OFF ratio. MEMS actuation voltage is more than that of I.Cs, graphene based Radio frequency electromechanical system switches may reduce actuation voltage to greater value.[11] The RF-MEMS switches are used...
for switching of radio frequency signals that covers a significant portion of electromagnetic frequency spectrum from 3 kHz to 300 GHz.

From last few years various researcher have worked for design, analysis, different geometrical models as well as different materials. V.B. Sawant et.al used Au as a membrane layer of switch and reported the voltage [12]. Yan-Qing Zhu et.al have complex design structure and shown 78 V actuation voltage [13] Such high actuation of voltage results less switching life. Pankaj Sharma et.al worked for graphene based RF-NEMS switch and recorded various scattering parameters [14]. We have done work in this paper to study low loss, low power consumption for electrostatic actuation, High isolation, high linearity. In the present work we have modeled RF-NEMS switch in which lowest actuation voltage is find out by varying dimension by analytically as well as numerically. Also scattering parameters are found out to report low insertion loss and high isolation so as to give better performance of switch than that of existing one. In this switch voltage is applied between the membrane and central conductor which gives the conductivity of membrane as well as actuation of the switch. In this study we have taken monolayer, bilayer and multilayer graphene for obtaining better performance of switch.

The graphene based RF-NEMS switch is shown in fig. The graphene membrane is attached between ground conductors, ground conductors are attached to low loss substrate material in this study.
we have used silicon which is highly resistive. There is central conductor which is in contact with thin dielectric layer, the dielectric layer is of Si$_3$N$_4$ we have used Si$_3$N$_4$ due to its high K value. This dielectric layer is used to avoid the short circuit between graphene membrane and bottom electrode. Mostly the dielectric layer is made very thin, in some switches it is reported from 1500 A to 2000 A [15-20]. Both the ground electrode and central electrode are made up of Au due to its high conductivity. Dc voltage which is applied across graphene membrane and central electrode causes the generation of electrostatic force this electrostatic force causes the membrane to change its position from up-state to down-state.

One interesting property of graphene is that its conductivity is tuneable we shown it in fig 3. And fig.4 there are two cases that is switch in upstate and second switch is in down-state that depends on actuation of switch.

When switch is not actuated the graphene beam will be in up-state position and having conductivity equal to $\sigma$-up. Similarly when the switch is actuated by applying actuation voltage between graphene membrane and central electrode switch will be in down position as shown in fig. 4 having conductivity equal to ($\sigma$-down). As in case of down-state the membrane is in direct contact with the dielectric layer, membrane feels electric field from bottom electrode which tunes the conductivity.

2. Modeling

2.1 Conductivity of graphene

According to kubo’s formula, by considering intraband contribution graphene conductivity may be as [21].
Here
\[ \omega = \text{Angular frequency} \]
\[ \mu_{c} = \text{Chemical potential} \]
\[ \Gamma = \text{Phenomenological scattering rate} \]
\[ T = \text{Temperature in k} \]
\[ k_B = \text{Boltzmann’s constant} \]

From (1) the graphene membrane has different values of chemical potential and phenomenological scattering rate in up-state and down-state position of switch. So in order to find out value of conductivity of graphene membrane we should know both \( \mu_{c} \) and \( \Gamma \) in both the states of switch.

### 2.2 Conductivities in up- and down-state positions

#### 2.2.1 Scattering rate

According to Matthiessen’s rule total scattering rate is given as

\[ \tau^{-1} = \tau_{gr}^{-1} + \tau_{sub}^{-1} \]  \hspace{1cm} (2)

Where
\[ \tau_{gr}^{-1} = \text{rate for graphene} \]
\[ \tau_{sub}^{-1} = \text{rate for substrate.} \]

Zhu et al.\textsuperscript{[23]} has shown that \( \mu \)-sub, is related to \( N_{op} \) by

\[ \mu_{sub} = \alpha n^{\alpha} N_{op} \]  \hspace{1cm} (4)

Values of \( \alpha \) and \( \text{Sox} \) is calculated experimentally where
\[ \alpha = 0.04 \]
\[ \text{Sox} = 0.141 \]

With the help of above equation, \( \tau_{sub} \) can be calculated by using below equation for monolayer and multilayer both.

\[ \tau_{sub}^{-1} = \frac{1}{\mu_{sub} m^{*}} = \frac{q^{2}}{\sigma m^{*}} \]  \hspace{1cm} (5)

\[ \tau_{sub}^{-1} = \frac{1}{\mu_{sub} h v_f} = \frac{q^{2} v_f}{\sigma h} \sqrt{n} \]  \hspace{1cm} (6)

\( \tau_{op} \) is the scattering rate in the up-state while \( \tau_{down} \) is for no influence of substrate in down-state can be taken as

\[ \Gamma_{up} = \tau_{gr}^{-1} \]  \hspace{1cm} (7)

\[ \Gamma_{down} = \tau_{gr}^{-1} + \tau_{sub}^{-1} \]  \hspace{1cm} (8)

Electron hole puddle effect and scattering by ionized impurities are not considered for this case, by annealing the sample such condition can be overcome.

#### 2.2.2 Chemical potential

From the equation it is clearly visible that chemical potential \( \mu_{c} \) (of monolayer graphene) is related to electron hole and carrier density \( n_{o}(n_{o}). \)

\[ \eta_{e} - \eta_{h} = \text{sign}(\mu_{c}) \frac{1}{\pi} \left( \frac{\mu_{c}}{h v_f} \right)^{2} \]  \hspace{1cm} (9)

where \( v_f \) is the fermi velocity grapheme which is equal to \( 10^{6} \text{ m/s}. \) While in case of multilayer

\[ \eta_{e} - \eta_{h} = \frac{2m^{*} \mu_{c}}{\pi h^{2}} \]  \hspace{1cm} (10)

Where,
\[ m^{*} \approx 0.052 m_{e} \]

\( m^{*} \) = effective mass of multilayer grapheme.
\( m_e \) = effective mass of electron.

Chemical potential of monolayer graphene in up-state position \( \mu_{c\text{ upMono}} \) with an initial hole (electron) carrier density \( n_{h\text{ up}} \) (\( n_{e\text{ up}} \)) is given by

\[
\mu_{c\text{ upMono}} = \text{sign}(\eta_{e\text{ up}} - \eta_{h\text{ up}}) \hbar v_f \sqrt{|\eta_{e\text{ up}} - \eta_{h\text{ up}}|} \pi. \tag{11}
\]

Similarly, the chemical potential of multilayer graphene in up-state position \( \mu_{c\text{ upMulti}} \) can be written as

\[
\mu_{c\text{ upMulti}} = \frac{\pi h^2}{2m^*} (\eta_{e\text{ up}} - \eta_{h\text{ up}}) \tag{12}
\]

By applying dc voltage \( V_{\text{bias}} \) between the central conductor and ground consider down-state position. The membrane is pulled towards the centre conductor by resulting electrostatic force and voltage at that moment is called pull-in voltage \( V_{\text{pull-in}} \). At \( V_{\text{bias}} \geq V_{\text{pull-in}} \), membrane is in direct contact with bottom dielectric layer. Membrane in region 2 at this position experiences field effect from central conductor. For calculating carrier density, charge balance relationship is given by

\[
V_{\text{bias}} - V_{\text{dirac}} = \frac{q(\eta_{e\text{ down}} - \eta_{h\text{ down}})}{c_{ox}} \tag{13}
\]

Where

\( q = \) elementary charge

\( n_{h\text{ down}} \) (\( n_{e\text{ down}} \)) = hole carrier density in down-state position

so the carrier density in the down-state condition is given by

\[
\eta_{e\text{ down}} - \eta_{h\text{ down}} = \frac{c_{ox}}{q} V_{\text{bias}} + \eta_{e\text{ up}} - \eta_{h\text{ up}} \tag{14}
\]

\[
\mu_{c\text{ downMono}} = \text{sign}(\frac{c_{ox}}{q} V_{\text{bias}} + \eta_{e\text{ up}} - \eta_{h\text{ up}}) \hbar v_f \sqrt{\left|\frac{c_{ox}}{q} V_{\text{bias}} + \eta_{e\text{ up}} - \eta_{h\text{ up}}\right|} \pi \tag{15}
\]

\[
\mu_{c\text{ downMulti}} = \frac{\pi h^2}{2m^*} \left(\frac{c_{ox}}{q} V_{\text{bias}} + \eta_{e\text{ up}} - \eta_{h\text{ up}}\right) \tag{16}
\]

3. Switch description

a. RF-NEMS switch actuation mechanism:

The formula that is used for actuation voltage is as follows,

\[
V_{\text{pull-in}} = \sqrt{\frac{8k}{27g_0W_w}} g_0^3 \tag{17}
\]

Here

\( k = \) Stiffness of membrane

\( g_0^3 = \) Height between the membrane and dielectric layer

\( W = \) width of centre conductor

\( w = \) width of graphene membrane

Spring stiffness constant is further given as

\[
k = 32 E_w(t/L)^3 + 17T/L \tag{18}
\]

\( E = \) young’s modulus of graphene layer

\( t = \) thickness in graphene membrane

\( L = \) Length in graphene membrane

\( T = \) axial tension in graphene membrane
In case of down-state better isolation is obtained due to its high chemical potential which leads to increase in conductivity.

Time required for switching is given by,

\[ t_s = 3.67 \frac{V_{\text{pull-in}}}{V_{\text{res}}} \]  \hspace{1cm} (19)

\[ V_s = 1.3 * V_{\text{pull-in}} \]  \hspace{1cm} (20)

\( \omega_0 \) = Angular resonant frequency

Where

\[ \omega_0 = \sqrt{\frac{k}{m_{\text{eff}}}} \]  \hspace{1cm} (21)

\&

\[ m_{\text{eff}} = 0.735 L^* w^* t^* \rho \]  \hspace{1cm} (22)

in which \( \rho \) = mass density.

b. Design:

The design parameters are varied in such a way that to get the minimum voltage and better isolation. Length of the switch is varied from 5 \( \mu \)m to 30 \( \mu \)m while the width and thickness are varied from 5 to 15 and thickness is from 0.34 to 2 nm. The gap height is taken as 300 nm where no any changes are made for gap height as that of Pankaj Sharma et. al.[14]. Dielectric material of thickness equal to 20 nm is used to get high capacitance ratio.

The dynamic behaviour of NEMS switch can be understood with the help of one dimensional model.

\[ m \frac{d^2x}{dt^2} + b \frac{dx}{dt} + kx = F_e \]  \hspace{1cm} (23)

Where,

\( m \) = the effective mass

\( F_e \) = Electrostatic force

\( b \) = damping coefficient

\( K \) = Stiffness

\( V_s \) = Actuation voltage

\( g_0 \) = Initial gap

![Fig.5 (a)Top view of switch](image)
The above equation is second order differential of nonlinear type. This equation is helpful for finding out the switching time and release time with or without consideration of actuation voltage. The time required to reach the beam from up-state to down-state is called switching time whereas the time required by the beam to come back to 10% of \( g_0 \) once the actuation voltage is removed is known as release time or pull-up time. By taking the condition of no damping that is \( b=0 \) with conditions i.e., \( x = 0 \) and \( dx/dt = 0 \) at \( t = 0 \), the switching time and release time can be obtained analytically. Though the equation obtained is not so accurate but it will help in finding out the dynamic behaviour of switch. As the equation is second order differential so it is difficult to get switching time and release time without \( b=0 \).

4. Result

The analytical and simulation works are carried out in order to get the minimum actuation voltage and better isolation with minimum insertion loss. For that we varied length, width and thickness to get the optimum design parameters.
Fig.7. Release time & Voltage as a function of Length for different values of beam thickness

From fig.6 it is clear that release time is inversely proportional to length. And it is observed that the release response time for length 10 µm is 80% more when it is compared to 30 µm length for switch of thickness 0.34 nm. For bilayer and multilayer thickness it is 66% more for both the layers. Fig.7 Shows that the variation of release time and voltage with length variation the optimum length (30 µm) and the thickness t=0.34 nm, 0.64 nm and 2 nm for design 1, 2 and 3 respectively. The dynamic response shows that the fast switching that is less than 300 ns for NEMS switch with length 30 µm shows actuation voltage of (<0.4 V). Ansys APDL and Ansys HFSS are used for dynamic and electromechanical behaviour of the switch. The beam is modelled using 3D element in Ansys APDL. The fig.8 shows the deflected part of beam. Modal analysis is done to get the resonant frequency of the switch. The maximum frequency above which structure will fail to operate is termed as resonant frequency. The beam is fixed to both the ends and when force is applied it get deformed as shown in fig.8.

We have done Simulation of graphene based membrane using Ansys HFSS (High Frequency Structural Simulator). This will help in finding out the insertion loss and isolation, for that S-parameters are computed with Frequency. Fig.9 shows the insertion loss and isolation as a function of frequency. Frequency that ranges from 1 to 60 GHz is used.

Fig. 8 Modal patterns of the beam structure for first mode.
Fig. 9 S-parameters of RF-NEMS switch in up-state for monolayer, bilayer and multilayer graphene.

It is noted that better RF performance is obtained for multilayer graphene. Isolation of -54 dB and insertion loss of -0.02 dB at 10 GHz is noted. Good RF performance will help in enhancing the switch performance.

5. Discussions

Various works have been done on NEMS/MEMS switches, but they are having either high insertion loss or high voltage or both. In this work, we have reported low actuation voltage that is less than 2 V. Actuation voltage is less for length 30 µm and width of 15 µm. The better isolation -54 dB and less insertion loss of -0.02 dB is obtained by simulation. The graph in this work shows fastest switching time. We have modified dimensions to get the better result. The outstanding RF-performance mark switches an appropriate choice for very high frequency uses.

6. Conclusion

It is concluded that graphene can be best material for RF-NEMS switches. It is shown that graphene based RF-NEMS switch is giving less insertion loss and lowest actuation voltage however fast switching is also noted as better results. These graphene based RF-NEMS switch can operate at high frequency. It is seen that multilayer graphene have better isolation that is -54 dB at 10 GHz than that of monolayer graphene.

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