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Pull-In Voltage Modeling of Graphene Formed Nickel Nano Electro Mechanical Systems (NEMS)

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Abstract—**Pull-in voltage model of nano-electro-mechanical system with graphene is investigated for the device optimization. In the pull in voltage model, thickness of graphene layer is assumed to be uniform in vertical and lateral direction. Finite element analysis simulation has verified the feasibility of the suggested model. From the suggested model, pull-in voltage change with graphene thickness and cantilever length can be estimated. Maximum induced stress and graphene thickness have a reciprocal relationship.**

Index Terms—**Nano electro mechanical systems (NEMS), graphene, modeling of graphene**

I. INTRODUCTION

Nano electro mechanical systems (NEMS) are considered as promising switching devices for a variety of electronic applications due to the zero leakage current and abrupt switching properties [1-6].

However metal based NEMS technologies have some problems such as static friction and abrasion that cause a failure of the electrical contact [7-9]. Graphene is theoretically suited for NEMS and has excellent mechanical properties, including high stiffness and low mass [10-13]. Graphene based NEMS overcome the static friction and help solving reliability problem of micro-electronic devices.

The integration research of graphene NEMS for high density circuits needs selective graphene growth methods. To solve the integration problem, graphene NEMs have been fabricated by using chemical vapor deposition (CVD) on nickel cantilever [14]. The precise control of graphene material on NEMs can be realized by the selective growth of graphene on the pre-fabricated metal beam.

Since the manufacturing of NEMS requires high cost and difficult processes, design optimization is necessary to reduce cost and trial-and-error time [15]. Pull-in voltage can be treated as the most important parameter for NEMS operation because it determines operation voltage and power dissipation. Prediction of pull in voltage with device dimensions can offer a guide line for NEMS design. In this paper, we proposed theoretical models for pull in voltage of NEMS, which is based on graphene with Ni cantilever.

II. SIMULATION STRUCTURE

In this work, NEMS simulations are performed with finite element analysis simulation. In the simulation work, cantilever is assumed to have rectangular parallelepiped beam structure as shown in Fig. 1(a). Fig. 1(b) shows dimensional parameters at the side view of cantilever. One of the cantilever's surface is fixed and another surface moves down to electrode. Fig. 1(c) shows the front side structure parameters of the cantilever for pull-in voltage modeling.

L_{beam}, T_{beam} and W_{beam} are the cantilever length, thickness and width respectively. G is the distance

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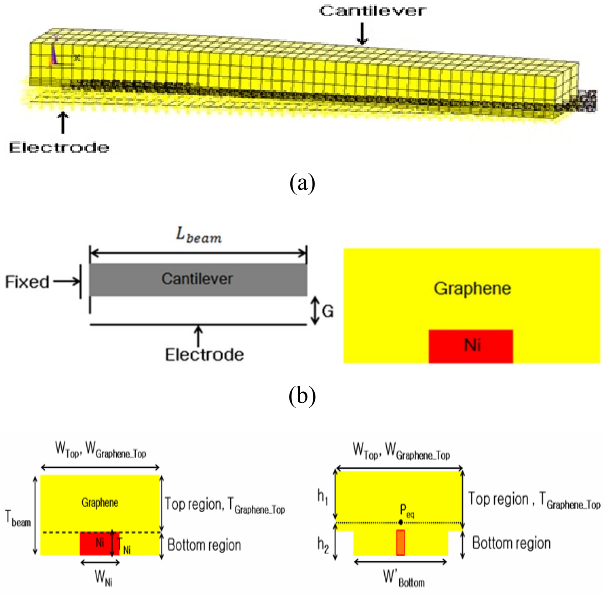

(a)

(b)

(c)

Fig. 1. (a) Vertical and lateral schematic diagram of NEMS with grapheme, (b) The equivalent structure of NEMS with graphene and dimensional parameters.

between the cantilever and electrode. $E_{Graphene}$ is the Young's modulus of graphene and the value of this parameter is cited from the previous work [16]. $T_{Graphene\_TOP}$ and $W_{Graphene\_Top}$ represent the graphene upper region thickness and width respectively. E_i is the Young's modulus of nickel. T_{Ni} and W_{Ni} are the nickel region thickness and width.

Since two different types of material properties are tied together, mathematical method for equivalent material is necessary to get the pull-in voltage. The moment inertia of two materials is merged into single structure for unified equation. It should be modified as shown in Fig. 1(c). The modified width of Ni is determined by the ratio of Young's modulus of Ni to graphene as shown in Eq. (1) [17-19].

$$\begin{aligned} n &= \frac{E_{Ni}}{E_{Graphene}}, W'_{Bottom} = nW_{Bottom} \\ &= \frac{E_{Ni}}{E_{Graphene}} W_{Bottom} \end{aligned} \tag{1}$$

To determine the moment of inertia at the center of the equivalent structure (P_{eq}), h_1 and h_2 are defined in an equivalent material structure through the Eq. (2) [19].

$$\begin{aligned} h_1 &= \frac{\sum yiAi}{\sum Ai} \\ &= \frac{\frac{1}{2}T_{Top}(T_{Top}W_{Top}) + (T_{Top} + \frac{1}{2}T_{Bottom})\frac{E_{Ni}}{E_{Graphene}}W_{Bottom}T_{Bottom}}{W_{Top}T_{Top} + \frac{E_{Ni}}{E_{Graphene}}W_{Bottom}T_{Bottom}} \\ &= \frac{\frac{1}{2}T_{Top}^2 W_{Top} + (T_{Top} + \frac{1}{2}T_{Bottom})W'_{Bottom}T_{Bottom}}{W_{Top}T_{Top} + W'_{Bottom}T_{Bottom}} \\ h_2 &= T_{Top} + T_{Bottom} - h_1 \end{aligned} \tag{2}$$

T_{Top} and T_{Bottom} are top region and bottom region thicknesses respectively as shown in Fig. 1(c).

Y_i is the distance from P_{top} to the bottom of the cantilever and A_i is the cross-sectional area.

Since the direction of motion of the two materials is the same, the moment of inertia of the equivalent structure can be determined by the moments of inertia, I_1 and I_2. Equation for moments of inertia is as follow Eq. (3).

$$I' = I_1 + I_2 \tag{3}$$

$I_1$is the moment of inertia of the top region of cantilever beam and I_2 is the moment of inertia of the bottom region of cantilever beam.

The moment of inertia of a rectangular structure is expressed by Eq. (4) [19].

$$I = \frac{Wt^3}{12} \tag{4}$$

The moment of inertia, I_1 andI_2 are calculated as

$$I_1 = I_{1c} + A_1 d_1^2, \quad I_2 = I_{2c} + A_2 d_2^2 \tag{5}$$

I_{1c} and I_{2c} mean the moments of inertia of the original structures and A_1 and A_2 are the cross-sectional areas of the equivalent structure. d_1 and d_2 are distances between equivalent structure center and the original structure center at top region and bottom region respectively as shown in Fig. 1(c) [19].

From Eqs. (2-5) the total moment inertia of equivalent structure can be expressed as Eq. (6).

$$
\begin{aligned}
I^{'} &= \frac{1}{12}W_{Top}T_{Top}^{3} + W_{Top}T_{Top}(h_{1} - \frac{1}{2}T_{Top})^{2} \\
&+ \frac{1}{12}\frac{E_{Ni}}{E_{Graphene}}W_{Bottom}T_{Bottom}^{3} \\
&+ \frac{E_{Ni}}{E_{Graphene}}W_{Bottom}T_{Bottom}(h_{2} - \frac{1}{2}T_{Bottom})^{2}
\end{aligned} \tag{6}
$$

The spring constant of the cantilever with a rectangular cross section is expressed in Eq. (7) [20].

$$
k_{c} = \frac{2}{3}EW\left(\frac{t}{l}\right)^{3} \tag{7}
$$

The spring constant can be expressed using the moment of inertia by Eq. (8) [20].

$$
k_{c} = Ix = \frac{wt^{3}}{12}x = \frac{2}{3}EW\left(\frac{t}{l}\right)^{3}, \quad x = \frac{8E}{l^{3}}, \quad k_{c}\,\frac{8EI}{l^{3}} \tag{8}
$$

By using the moment of inertia of the equivalent structure from Eq. (6), the modified spring constant is expressed as Eq. (9).

$$
k_{c}^{'} = \frac{8E_{Graphene}I^{'}}{L_{Graphene}^{3}} \tag{9}
$$

The pull-in voltage of the cantilever is calculated by using Eq. (10) [21].

$$
V_{PI} = \sqrt{\frac{8k_{c}}{27\varepsilon_{0}W_{Top}L_{Top}}G^{3}} \tag{10}
$$

Here ε_0 is the vacuum permittivity and G is the distance between the cantilever and the electrode.

The final equation for pull-in voltage for cantilever is expressed as Eq. (11).

$$
V_{PI} = \sqrt{\frac{64E_{graphene}\left[\begin{aligned} &\frac{1}{12}W_{Top}T_{Top}^{3} + W_{Top}T_{Top}(h_{1} - \frac{1}{2}T_{Top})^{2} \\ &+ \frac{1}{12}\frac{E_{Ni}}{E_{Graphene}}W_{Bottom}T_{Bottom}^{3} \\ &+ \frac{E_{Ni}}{E_{Graphene}}W_{Bottom}T_{Bottom}(h_{2} - \frac{1}{2}T_{Bottom})^{2} \end{aligned}\right]}{27\varepsilon_{0}W_{Top}L_{Top}^{4}}G^{3}} \tag{11}
$$

IV. RESULTS AND DISCUSSIONS

Fig. 2 shows comparison results between simulation and model when they have variation in graphene width and thickness. The width and thickness variation of graphene shows quadratic relationship with pull-in voltage. Even though there is some quantitative differences between the model and simulation results, the tendency of the pull-in voltages are matched with each other as shown in Fig. 2. Effect of graphene deposition thickness is shown in Fig. 2. From Eq. (11), pull-in voltage slightly increases with graphene thickness. Similar is the result in Fig. 2, difference between model and simulation results increase with graphene thickness. Because the thick graphene can cause high pull up voltage operation, our model can be applied to NEMS modeling with thin graphene.

The difference between simulation and model result is caused by limitation of estimation method [22]. The analytical model assumes a flat cantilever and electrostatic force is assumed to be uniformly distributed over it. Due to uniform electrostatic force distribution, the pull in voltage difference is inversely proportional to the beam length as shown in Fig. 3. Additional research is needed to reduce the quantitative difference between simulation and modeling result.

Although the aggressive scaling down of beam length is hard to be achieved in real fabrication. The difference between model and simulation results is tolerable in real fabrication. In the optimization of NEMS design,

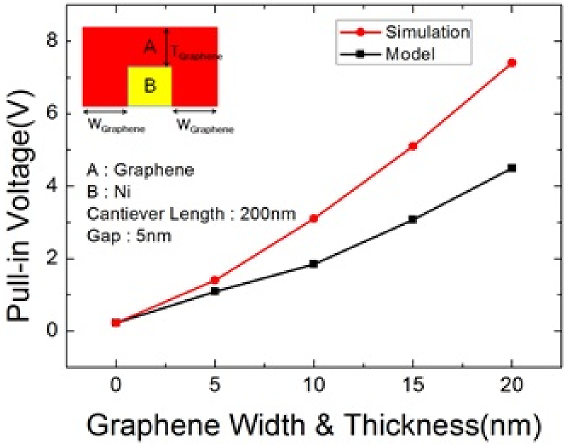

Fig. 2. Pull in voltage comparison between suggested model and FEA simulation result in accordance with graphene thickness variation. Cantilever length is fixed at 10 nm.

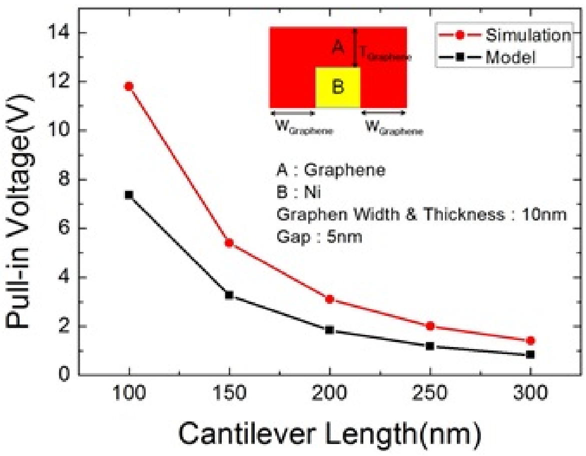

Fig. 3. Pull in voltage comparison between suggested model and FEA simulation result in accordance with cantilever length variation. Graphene thickness is fixed at 10 nm.

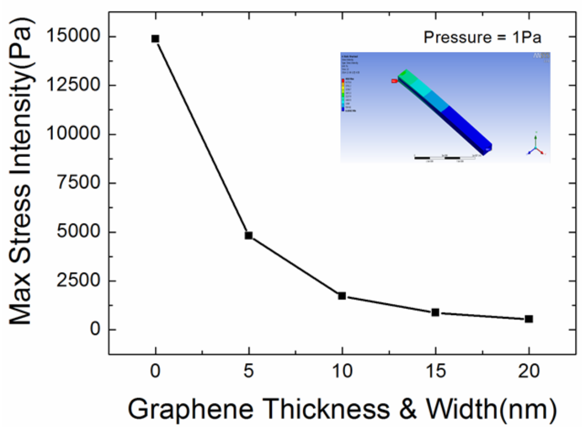

Fig. 4. Maximum stress values on NEMS accordance with graphene thickness variation.

graphene thickness should be carefully considered. Even though thin graphene NEMS has small pull in voltage but thin graphene can also causes high stress in NEMS. Fig. 4 shows maximum stress of NEMS with graphene thickness variation. Every NEMS has 200 nm length and 1 Pa force is induced to flexible surface of NEMS. As shown in Fig. 4, maximum stress on NEMS decreases with graphene thickness. From this result, thickness of NEMS should be optimized with careful consideration of pull-in voltage and reliability.

V. CONCLUSIONS

In this paper, analytical modeling of NEMS pull-in voltage has been proposed for the accurate evaluation of NEMS operation. In particular, the modeling is performed to NEMS device which uses a Ni cantilever as a catalyst of graphene layer. The suggested pull-in voltage model for the NEMS provides a good accuracy when NEMS has long length and thin graphene. Pull in voltage modeling indicates that the graphene thickness has a significant role in determining the pull-in voltage and reliability of NEMS. The graphene thickness should be carefully considered for NEMs design optimization. As graphene thickness increases, pull-in voltage increases. However increase of graphene thickness reduces maximum stress intensity in NEMS cantilever. Our model and simulation results can offer insights of graphene NEMS device optimization.

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