FINITE ELEMENT METHOD ANALYSIS OF ELECTRIC FIELD INDUCED PULL-IN DEVIATION IN NEM CONTACT SWITCHES

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Abstract - *The miniaturization trend leads to the development of a graphene based Nano Electro Mechanical (NEM) switch to fulfill the high demand in low power device applications. In this article, we highlight the Finite Element Method (FEM) simulation of the graphene-based NEM switches of fixed-fixed ends design with beam structures which are perforated and intact. An external mechanical, electrical, or chemical stimulus can be detected and measured, and a response to the stimulus can be produced. Pull-in and pull-out characteristics are analyzed by using the FEM approach provided by COMSOL software.*

Key Words: Graphene, Pull-in deviation, Graphene analysis, Nano Electro Mechanical switch, COMSOL simulation, Finite Element Method simulation.

1. INTRODUCTION

A Nano Electro Mechanical (NEM) switch is one of the promising devices to solve the problems of high power consumption in complementary metal-oxide semiconductor (CMOS) circuits. The NEM switch is built into logic circuits, relays, data storage, and high frequency communication because of its high ON-OFF current ratio and low leakage current. Graphene is one of the suggested 2D materials for high-performance NEM switch application because of its superior properties namely high electron mobility excess of 200,000 cm, superior current density capacity of 108 A/cm, the ultra-thin thickness of 0.335 nm and low resistivity of 1 W/cm. For these reasons, graphene-based NEM switch can provide better reliability and lower actuation pull-in voltage than a conventional switch.

1.1 Device geometry

In this section, we briefly describe the geometry and operation principles of NEM switches. In our earlier work, we experimentally studied the switching operation of Nano Crystalline Grapheme (NCG) beam NEM switches. The NCG was synthesized by direct deposition of NCG on a Si/SiO2 substrate using Plasma-Enhanced Chemical Vapor Deposition (PECVD).

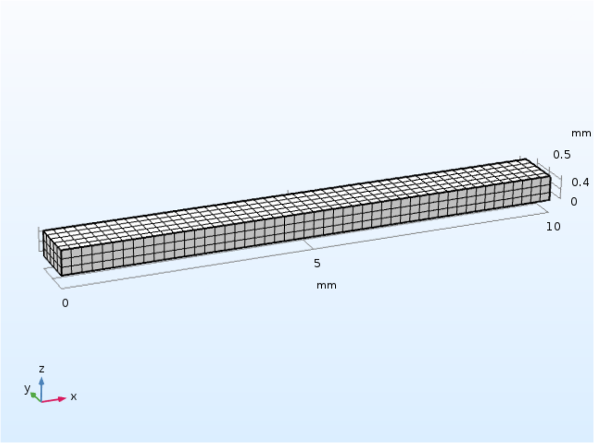

Fig -1: Structure of the beam

The NCG deposited by PECVD contains both sp2- and sp3-hybridized carbon atoms. The deposited NCG film is polycrystalline in nature. The polycrystalline nano graphene has randomly distributed grain orientation and size. The mechanical behavior of NCG depends on both the grain disorientations and the grain boundary rotation. Moreover, the mechanical strength of NCG depends on the arrangement of the defects in the NCG film. The NCG sheets have almost constant fracture stress and strain, and the fracture strength is independent of the grain size.

1.2 Switching methods

Self-aligned trench formation. The bottom electrode was intentionally over etched into the substrate, using the bottom electrode as a self-aligned etch mask. An SiO2 film deposited on the pre-patterned trench then formed the spacer structure, the thickness of which on the side edge of the bottom electrode was much less than that the top electrode was subsequently formed on the SiO2 spacer structure, which was later removed to create an air gap between the top and bottom electrodes (the profile of the air gap therefore being. We found that the depth of the trench and the deposition method are major tuning parameters for determining the profile of the sacrificial layer, which, in turn, determines the air gap structure. The proposed process can provide an extremely smooth surface on the side wall of the trench due to the planarization effect of the etching process.

2. GRAPHENE NEM SWITCH CHARACTERISTIC

The static electrical and mechanical characteristics of the NEM switch were simulated using the FEM-based analysis in COMSOL. Figure-1 shows a schematic of our graphene beam NEM switch with a graphene beam connected to electrodes at each end. This graphene beam NEM switch features a metal top gate (actuation electrode), which enables the graphene beam to be pulled onto the gate when a voltage is applied, and then pulled away, disconnecting from the channel when voltage is no longer applied. In order to be consistent with our experimental device structure, we used the device dimensions.

2.1 VON MISES stress analysis

The von Mises yield criterion is a general way to estimate the yield of any ductile material, such as metals. The mechanical reliability of the graphene beam NEM switch can potentially be improved by properly choosing the switch dimensions. To quantitatively demonstrate the mechanical reliability of the double-clamped graphene beam NEM switch, we compared the maximum von Mises stress exerted along the length of the graphene beam. The von Mises stress profile analysis is essential to comprehend the spatial variation of the stress generated on the suspended graphene owing to the applied voltage. A Cartesian coordinate system is used to represent the numerical coordinates on the suspended graphene beam. The stress profile was obtained after the pull-in state was achieved, giving the three-dimensional stress profile for the deformed graphene beam. However, the stress variation along the thickness is constant. The von Mises stress reaches the maximum value towards the ends of the graphene beam. When the length of the graphene beam is reduced, the von Mises stress is increased to the maximum value. As evident the device with the shortest graphene beam length has the maximum probability of failure. When the thickness of the graphene beam is scaled for the fixed length of the beam, the von Mises stress is reduced as the thickness is reduced.

2.2 Three-Dimensional electric field

To analyze the impact of the applied electric field on the double-clamped graphene beam NEM switch, we made the same model in COMSOL Multiphysics. The NEM switch was built inside a vacuum environment. The model was meshed with triangular mesh elements to reduce the computational complexity. The density of the mesh was varied adaptively in order to study the structural displacement of the graphene beam. In this simulation, the actuation electrode was kept at the bottom and the graphene beam was placed at the top. For the electric field analysis at different voltages, a constant bias of 0 V was applied to the bottom electrode (Au) and the voltage applied at the top electrode (graphene beam) was swept. The potential, V, and the electric field, E, in the free space can be obtained by solving Poisson's equation. The cross-sectional view of the electric field distribution across the center of the NEM switch for the applied voltage of 1V to the bottom electrode. The dimensions of the grapheme beam are equivalent to those of NEM switch.

3. MODELLING NEMS DEVICE

The elastic cantilever beam is an elementary structure in MEMS design. This example shows the bending of a beam due to electrostatic forces. The primary problem the model addresses is the 2-way coupling between the deformations and the electric field and how it affects the stability and impedance of the device. The model solves the electrostatic equation in the air domain surrounding the beam using the Arbitrary Lagrangian-Eulerian (ALE) method to account for geometry changes associated with the deformation. There are two versions: a 2D model and a 3D model. The 2D model uses the Plane Strain and the Electrostatics application modes from the MEMS Module and then the Moving Mesh (ALE) application mode from COMSOL Multiphysics. The 3D model uses the Solid, Stress-Strain application mode for the structural part.

3.1 Displacement of the beam

The suspended pipe clip structure and the bottom electrode behave as two parallel plates. The spring constant of the suspended beam was estimated using the, Young's modulus (450 G Pa), t is the thickness of the beam, l is the length, and w is the width of the beam. The resonance frequency was derived. A positive feedback exists between the electrostatic forces and the deformation of the cantilever beam. The forces bend the beam and thereby reduce the gap to the grounded substrate. This action, in turn, increases the forces.

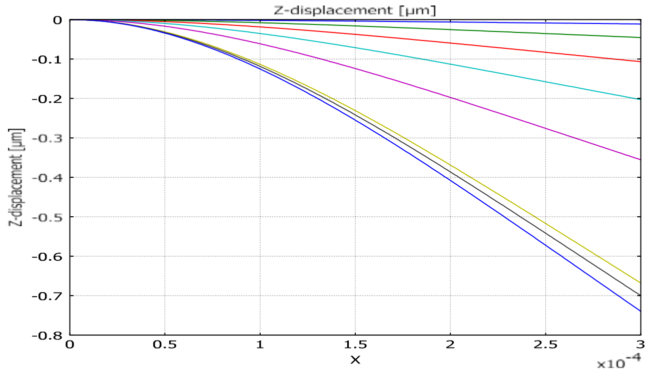

Fig -2: Deflection in edges of beam

At a certain voltage the electrostatic forces overcome the stress forces, the system becomes unstable, and the gap collapses. This critical voltage is called the pull-in voltage. At applied voltages lower than the pull-in voltage, the beam stays in an equilibrium position where the stress forces balance the electrostatic forces.

Figure 2 shows the potential field and the deformations for the 3D case. Figure 3 shows the shape of the cantilever's deformation extracted from 3D results along the long edge for different applied potential values. When solving for a level higher than the pull-in voltage, the solution ceases to converge before the beam touches the substrate. This is an effect of the ALE method not being able to handle topology changes. By scanning over different applied voltages and using the parametric solver, you can study the beam's behavior and estimate the pull-in voltage.

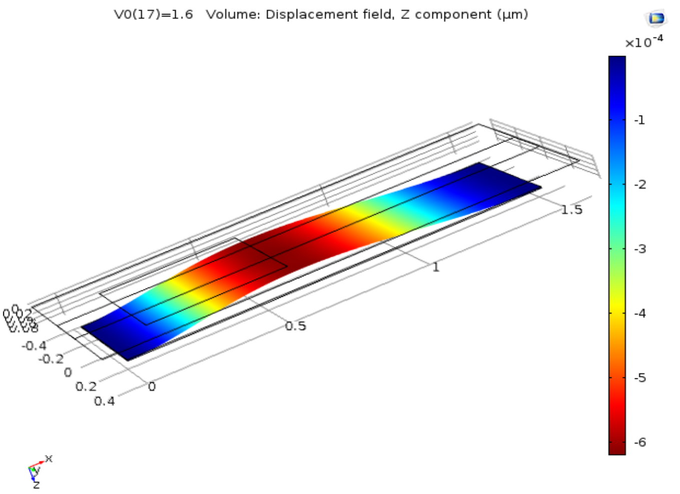

Fig -3: Displacement of the beam

3.2 Analysis of pull-in voltage

The actuation pull-in voltage between intact and the perforated graphene beam NEM switch is compared. The results showed that the introduction of the perforated graphene beam structure reduced the actuation pull-in voltage by approximately ~9–32%. The perforation concept in the graphene beam structure reduced the beam mass and spring constant that lead to low beam stiffness. Simultaneously, the perforation eased the beam deflection and reduced the actuation pull-in voltage. The variation of beam length reduced the actuation pull-in voltage because of the reduction in beam mass and volume which changed the beam spring constant corresponding to Young's modulus of the graphene beam. In addition, the pull-in voltage value with lower dimension can still be reduced by adding the holes in the graphene beam as more spaces becomes available with the decrease in length, thus reducing the graphene beam stiffness. However, the variation of width did not affect the actuation pull-in voltage because the beam stress was only induced at the cross-section area of the beam thickness and length without involving the width. The hysteresis value is also reduced by approximately ~25% for the 12-column perforated grapheme beam structure, 1.5 _m of graphene beam length, 3.0 nm of graphene beam thickness, and 70 nm of air gap thickness. This reduction was attributed to the reduction in effective area at the contacts interface between the perforated graphene beam and bottom actuation electrode. We also validated these models with the analytical expression by calculating the pull-in voltages based on the perforated NEM switch dimensions. The trends from the analytical models compared well with the FEM simulations results for the perforated graphene-based NEM switch.

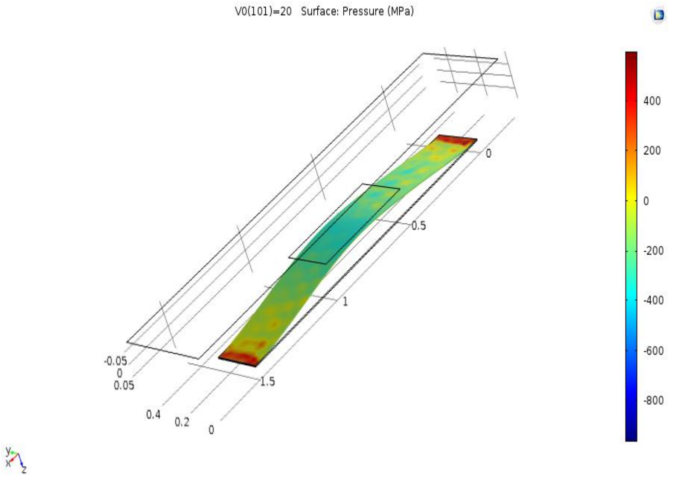

Fig -4: Surface pressure of the beam

4. CONCLUSION

The characteristics of a beam are plotted for different values. These characteristics are graphed for different values. These characteristics says that resonant frequency is directly proportional to beam thickness and inversely proportional to beam length. It is also demonstrated that while monolayer graphene results in quite high switch losses at high frequency, the use of multilayer graphene, can considerably reduce the switch losses and improve the RF performance. Finally, an equivalent circuit model for the graphene-based RF NEMS switch is extracted and the results are compared with the full-wave 3-D electromagnetic simulation.

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