Design and simulation of a compact low-stiffness MEMS-gate for Suspended-gate MOSFET

Richik Kashyap[1], S.Baishya[2] and Johnson Taye[3]

[1,2,3]Electronics and Communication Engineering Department, National Institute of Technology Silchar (NITS),Silchar,Assam 788010,India

Corresponding Author Email: rknits2010@gmail.com

Abstract

In this paper, first of allsome of the design aspects of fixed-fixed beam MEMS switchesare being cited and reviewed and based upon the related mechanics involved, we have developed a new compact architecture for the mobile gate that should be adopted for a low actuation voltage Suspended-Gate MOSFETalong with faster switching. A suspended Au metal beam of thickness 0.6μm with serpentine flexure hinges can be used as a mobile gate for the SG-MOSFET, whose length and width exactly equals the gate-length and width of the MOSFET and thus having no support structures outside the MOSFET's substrate domain, resulting in the compactness of the device. Altogether, the use of serpentine folded suspension, defining small holes in the Au beam, use of additional ground electrodes just below the folded suspension for extra electrostatic pull on the beam apart from the MOSFET channel (behaving as a ground plate), and maintaining an air-gap of 1.5μm for excellent isolation in 'off' state are the proper design considerations for a reliable and compactSG-MOSFET MEMS switch, being investigated in this paper.

Keywords: *Microelectromechanical Systems (MEMS), Suspended-Gate MOSFET (SG-MOSFET), MOSFET, Pull-in Voltage, Pull-down Ground Electrodes, Spring Constant, Switches,* Fringing*Fields, Residual Stress, Squeeze Film Damping, Damping Coefficient, Quality Factor 'Q'.*

1. Introduction

With the vast growth of portable wireless system, today MEMS devices have become the frontiers in the field of microelectronics because of the successful integration of microelectromechanical components with the Silicon (Si) and GaAs electronics and also for the post-CMOS compatibility. Due to the compatible micromachining process, it is now possible to realize a complete system-on-a-chip, wherein the integrated circuits play the role of decision making sub-systems and the MEMS actuators on the chip follow the instructions with their electromechanical movements like moving, positioning, regulating, pumping, and filtering. MEMS devices have paved a new way of development of low noise and low power based systems based on tunable antennas, oscillators, filters etc. and also contributed to the low loss RF switches, high-Q inductors, varactors and resonators. SG-MOSFET is a MEMS switch in which the mobile gate under electrostatic pull comprises the actuation part and the intrinsic MOSFET beneath it is the sensing element. SG-MOSFET switches are good for isolation (due to presence of air-gap between the mobile gate and the channel) and also enable faster switching, low standby power consumption. Moreover, compared to conventional MEMS beam switches, there is no question of micro-welding effect or permanent sticking problem of the switch since signal does not passes through the beam as in usual MEMS switches but here the signal passes through the MOSFET channel and the suspended beam is just required to switch ON and OFF the intrinsic MOSFET. Due to abrupt mechanical displacement of the mobile gate under the influence of electrostatic forces, a sub-threshold swing close to 2mv/decade [1] can be achieved in case of SG-MOSFET, compared to 60mv/decade swing limitation of conventional MOSFET.

In this paper, we have reviewed the basic design considerations for having a low effective spring constant and faster switching fixed-fixed beamMEMS switch that can be used as a mobile gate for SG-MOSFET. Also we have proposed on a new compact architecture and model geometry considerations for designing a low actuation voltage compact SG-MOSFET.

2. Theory of operation and design aspects

The SG-MOSFET is a MOSFET with a mobile fixed-fixed beam gate being placed over the top of the gate portion of the MOSFET. Whenever the actuation voltage is applied, the mobile gate is pulled down under the influence of electrostatic forces and the device goes to the ‘on’ state. The electromechanical model of the our proposed SG-MOSFET model (Fig.4(b)) can be best demonstrated in the Fig.1.The MOSFET channel and the additional pull-down ground electrodes in our model together exert electrostatic force on the Au metal beam, used as the mobile gate. Au metal is used as it has a low order Young Modulus. SiO2 insulation is provided above the ground electrodes in order to avoid the contact of the collapsed beam with the ground electrodes during complete pull-down. The restoring elastic force of the beam $F_{elastic}$ is modeled as an equivalent spring of spring constant k. The force equation governing the movement of the beam can be described as [2]:

$$|F_{elastic}| = kx = \frac{\varepsilon_{air} A (V_g - V_{Gint})^2}{2(t_{gapo} - x)^2} = |F_{electrostatic}| \qquad (1)$$

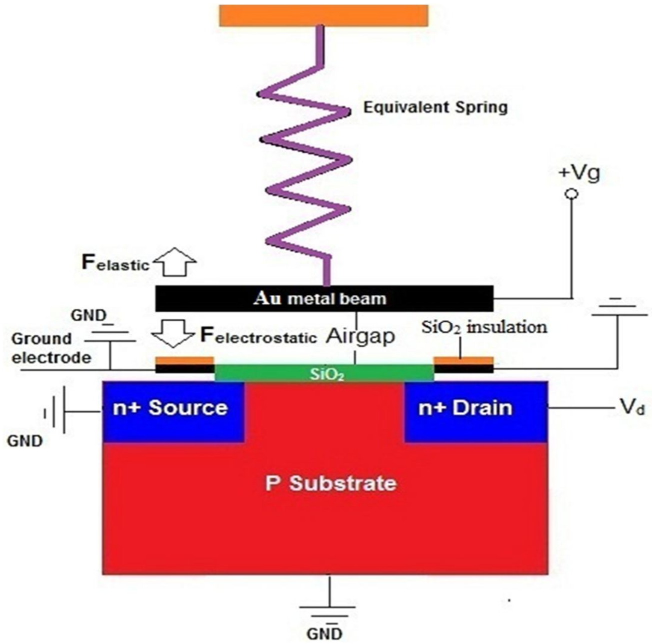

Fig.1:Simplified electromechanical equivalent model of SG-MOSFET

, where x is the gate displacement, t_{gap0} is the initial air-gap dimension and V_{Gint} is the intrinsic gate voltage. The unstable equilibrium condition is reached at $x = t_{gap0}/3$. The pull-in voltage V_{pi} is expressed as [3]:

$$V_{pi} = \sqrt{\frac{8k}{27\varepsilon_0 W_{beam} L_{beam}} t_{gap0}^3} \qquad (2)$$

, where W_{beam} and L_{beam} are the width and length of the beam. Thus, in order to have a low voltage device, the pull-in voltage needs to be low and for which the spring constant and the air-gap should be small if the area of the beam is kept constant. But reducing the air-gap beyond 0.2μm [2] is not a good design consideration keeping in mind the isolation factor in the 'off' state. Hence, we have proposed a serpentine flexure hinge design for the suspended beam in order to bring down the effective spring constant to a lower value and also for the compactness of the device. Using the serpentine flexure design aspects, the effective spring constant 'k' can be expressed [4] as:

$$k \approx \frac{48GJ}{l_a^2\left(\frac{GJl_a}{EI_x}+l_b\right)n^3}, \text{ for } n \gg \frac{3l_b}{\frac{GJl_a}{EI_x}+l_b} \qquad (3)$$

and J in Eq.3 is the torsion constant, given by:

$$J = \frac{1}{3}T^3 W_{beam}\left\{1 - \frac{192}{\pi^5}\frac{T}{W_{beam}}\sum_{i=1, i_{odd}}^{\infty}\frac{1}{i^5}\tanh\left(\frac{i\pi W_{beam}}{2T}\right)\right\} \quad (4)$$

, where T is the thickness of the beam, n is the number of meanders in the serpentine flexure, E is the Young Modulus of the material of the beam, $I_x = \frac{W_{beam}T^3}{12}$ is the moment of inertia, l_a and l_b are the corresponding lengths of the arms in the serpentine flexure shown in Fig.2, $G = \frac{E}{2(1+\vartheta)}$ is the torsion modulus and ϑ is the Poisson's ratio.

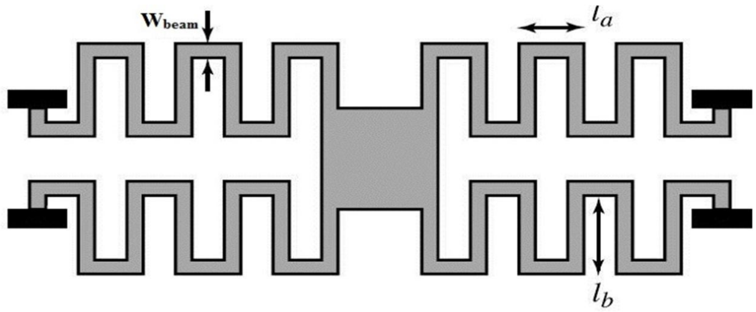

Fig. 2: Serpentine flexure support beam to reduce the effective spring constant.

The value of spring constant 'k' (Eq.3) can be decreased if we increase the number of meanders and the values of l_a and l_b. In our model, the value for the l_a and l_b are chosen in a way such that it reduces the spring constant in one hand and are designed not to cross the perimeter of the MOSFET's substrate, so as to account for the compactness of the device on the other hand (Fig.4(a,b,c))). The spring constant for a fixed-fixed beam generally depends on the stiffness of the suspended beam and also on the biaxial residual stress, σ_0(Pa), within the beam and is a result of the fabrication process. Due to biaxial residual stress, a additional elastic force S acts on both the beam ends, given by [4]:

$$S = \sigma_0(1-\vartheta)TW_{beam} \qquad (5)$$

, which increases the effective spring constant of the beam. By inclusion of circular or rectangular holes (of diameter or length of 3-8 μm) in the suspended mobile gate, the residual stress can be effectively reduced to $\sigma = (1-\mu')\sigma_0$, where μ' is the ligament efficiency given by $\mu' = \frac{l}{pitch}$,where l and $pitch$ are the distance between the perimeter and the centre of the nearest holes. The inclusion of holes does not affect the electrostatic pull on the beam since the fringing fields fill the area of holes but at the same time, reduces the mass of the beam which makes the pull-up of the beam easier during the 'off' state.

The dynamic response for a fixed-fixed beam can be demonstrated by famous d'Alembert's principle as:

$$f_{ext} = m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx \qquad (6)$$

, where x is the bridge displacement, m is the bridge mass, b is the damping coefficient, k is the spring constant, and $f_{ext}$is an external force. Taking the Laplace transform of the Eq.6, the frequency response is found to be dependent on a quality factor, given by $Q = {}^{k}/_{w_0 b}$, where $w_0 = \sqrt{{}^{k}/_{m}}$ is the resonant frequency. $Q \leq 0.5$ results in a slow switching time,while a $Q \geq 2$ results in a longer settling time when the switch is released. The value of Qshould be close to 1 for a better choice of having switching and release times [5]. The quality factor for a fixed-fixed beam is given as [4]:

$$Q_{ff} = \frac{T^2\sqrt{E\rho}}{\mu\left(\frac{W_{beam}L_{beam}}{2}\right)^2} t_{gap0}^3 \qquad (7)$$

, where μ is the coefficient of viscosity and ρ is the density of the material of the beam. For $Q \geq 2$, the switching time is given by $t_s \approx 3.67\frac{V_p}{V_s w_0}$. Generally the applied actuation voltage, $V_s$is kept from 1.3 to 1.4 times of the pull-in voltage,V_p to have a faster switching time and a reasonable operating voltage level suited for the system at the same time. However for the case of damping limited systems ($Q \leq 0.5$), assuming a constant external force and constant velocity approximation, the estimate switching time is given as [4]:

$$t_s = \frac{2bt_{gap0}^3}{\varepsilon_0 V_s^2} \qquad (8)$$

$$\approx \frac{27V_p^2}{4w_0 Q V_s^2}\text{ , for } V_s \gg V_p \qquad (9)$$

From the expression of t_s (Eq.8), it is evident that the switching time is directly proportional to damping coefficient ‘b’. Defining holes in the beam reduce the damping coefficient and hence increase the switching speed of the MEMS switch.

3. The proposed model

In this paper, we have proposed a new compact architecture for the mobile suspended-gate in SG-MOSFET(Fig.4(a,b,c)). A SEM image (Fig.3) of an usual SG-MOSFET has been referred to point out the support structures (typed in yellow colored scripts and lines) of the suspended beam, which are placed primarily above but outside the MOSFET’s source, drain and channel regions, thereby making the overall MOSFET an unnecessarily bigger object.In contrast to conventional SG-MOSFET design as shown in SEM picture,our model has no support structures outside the MOSFET domain and also we have maintained an air-gap, t_{gap0} =1.5μm ≫220nm. The use of serpentine flexure hinges for the beam results in both low pull-in voltage and compactness for the device. Also, the use of additional pull-down electrodes just below the beam ends together with the MOSFET channel contributes to the low pull-in voltage. Square holes are defined in the mobile gate specially to reduce the squeeze film damping and massof the beam and thus to increase the switching speed.

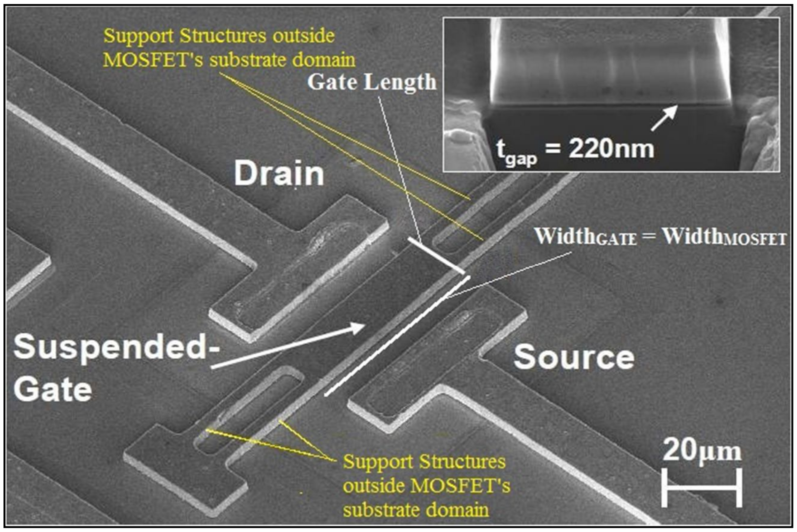

Fig.3: SEM image ofa SG-MOSFET [6]

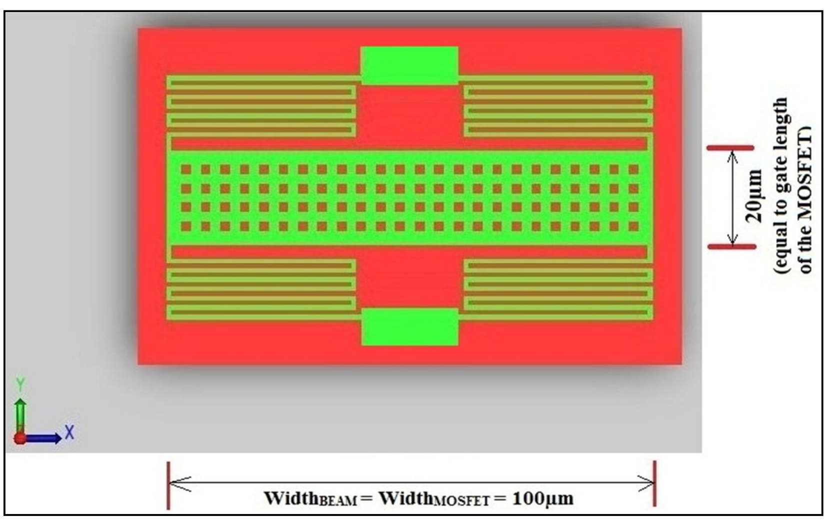

Fig.4(a): Top view of the proposed model of suspended mobile gate for SG-MOSFET in COVENTOWARE.

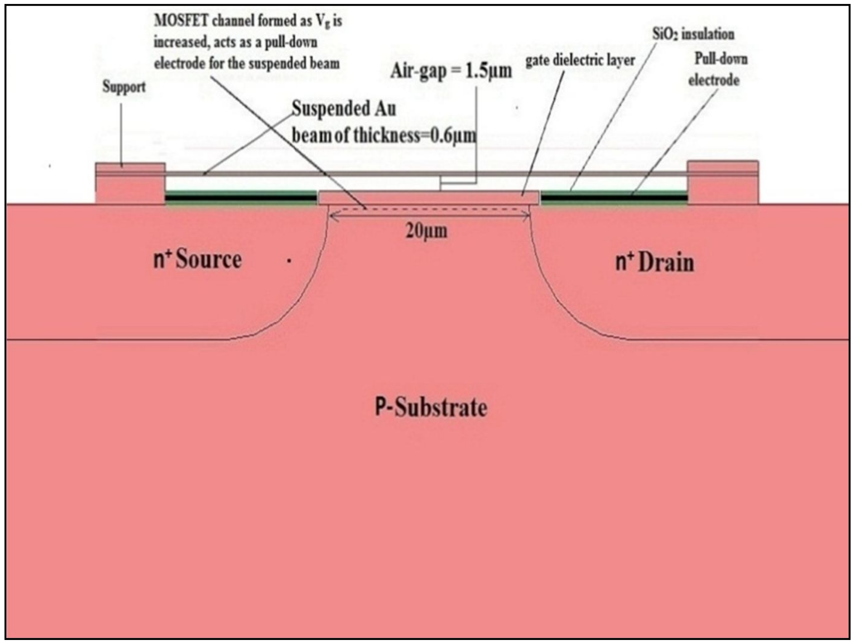

Fig.4(b): Cross-section of the n-channel SG-MOSFET, with the mobile gate beam of thickness 0.6μmsuspended with an air-gap of 1.5μm.

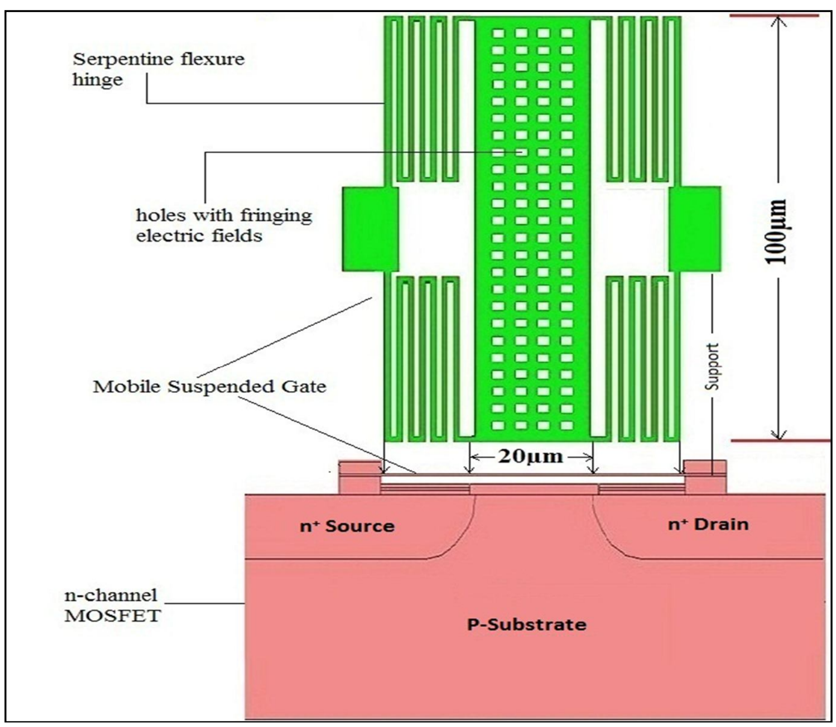

Fig.4(c): Combined view of cross-section of the SG-MOSFET and the top view of suspended mobile gate pinpointing the corresponding points and positions.

In our design, we have used a rectangular Au metal beam, which has thickness of 0.6µm, length of 20µm and width of 100µm, as the suspended mobile gate for the n-channel SG-MOSFET. The beam is supported by four serpentine flexure hinges at its four corners and is suspended maintaining an air-gap of 1.5µm above the gate dielectric layer which is far above the minimum requirement of 0.2µmfor having good isolation in the 'off' state. We know, the pull-in voltage depends on the 3/2th power of air-gap factor (Eq.2) and hence increasing the air-gap increases the pull-in voltage. However, the use of serpentine flexure hinges for the beam reduces the spring constant to a very low value which compensates for the air-gap dependence factor. Normally, an upper electrode is to be used for a very low spring constant beam during pull-up in the 'off' state since the restoring elastic force of the beam is now insufficient to regain its original position due to very low spring constant. But in this paper, we are basically concerned with having a compact suspended gate with low actuation voltage and hence no upper electrode has been used here to investigate the release of the beam in the 'off' state.In the cross-sectional view of SG-MOSFET (Fig.4(b)) , the black coloured stripe above the drain and source ends represents the additional pull-down electrodes surrounded by the up and down layer of SiO_2 insulation shown in green coloured stripes. These electrodes are kept within the insulation layers in order to avoid contact of the suspended mobile gate during pull-down and also to avoid the influence of grounding at the upper layer of source and drain ends.

4. Numerical Simulation

We have separately simulated the suspended mobile gate in COVENTOWARE in order to investigate its pull-in voltage, The mobile gate is applied a positive voltage and an equivalent pull-down ground electrode is used to represent altogether the MOSFET channel and the addition pull-down electrodes used originally in our model.

4.1 Design Process and Simulation Methodologies:

The proposed model of the suspended mobile gate for the SG-MOSFET is designed in COVENTORWARE, a widely used MEMS tool. The model is prepared with the help of process editor in COVENTORWARE. The processes involved follow the fabrication steps for microelectronics design. The first step is the selection of a substrate which will form the base of the structure. This provides the mechanical support to the structure. The thickness is 50 µm. Then the layout of the substrate is prepared in the layout editor wherein the length and breadth are decided (it actually doesn't affect the overall design but eases the simulation). The next step involves the deposition or etching of a dielectric layer (Si_3N_4) of 0.2μm thickness and covers the surface of the substrate. This layer separates the substrate as a ground from the mechanical structure as required for simulation. A 1.65μm sacrificial layer is deposited next. Material used is BPSG. In the next step the anchor space are cut out in the BPSG layer followed by the deposition of a 0.6μm thick Gold layer. This layer is the mechanical layer and is deposited using the planar fill step in the process editor. The serpentine flexure of the structure is carved out in the layout editor by using the straight cut mask in the process editor. This step resembles the lithography process in fabrication procedure. At last the sacrificial layer is deleted using the delete process if the process editor, which follows the lift-off procedure of fabrication. Thus the serpentine flexure based beam is extracted.

The simulation of the designed switch is performed in COSOLVE for MEMS simulation. The simulation is done in order to find the pull-down voltage of the switch, i.e. the voltage at which the suspended beam snaps down to the ground. The software uses the FEM method to simulate MEMS structures. In order to simulate the switch, meshes are created on the device for the FEM analysis. The parts selected for the simulation are the substrate and the suspended beam. Meshes are created on both the parts and are defined as still or moving. After the mesh is created, the structure is called in COSOLVE for the simulation. An increasing positive voltage is applied to the beam and the substrate is grounded. After the settings are done the simulation is started for the pull-down voltage. The simulation follows the Newton's iteration method. The iteration stops when the pull-down voltage is achieved.

4.2Simulation Results and Discussions:

The COVENTOWARE usually meshes the structure into a large number of small finite area elements for FEM numerical analysis. The colored surface plot obtained after simulating the structure, as shown in Fig.5, shows the relative displacement of various portions of the beam, when the bending of beam occurs under the influence of electrostatic pull as voltage at the beam is gradually increased in steps of 1 Volt. 1.65μm is the initial height of the beam from the substrate being grounded, where a small dielectric layer of 0.15μm is planted over the substrate just to avoid the contact of the beam with the grounded substrate, thus providing an air-gap of 1.5μm. The red colored portion of the simulated structure of the beam (area of 20×100 μm^2) is the actual portion of the switch that will lie exactly above the MOSFET channel in the original structure of SG-MOSFET and here in the plot it shows the maximum displacement of 1.5μm at 3[V] (Fig.6). However, the exact pull down voltage is somewhere between the lower bound and the upper bound voltage (Fig.7). For approximation we have taken upper bound of 2.75[V] as the pull-down voltage. We can see that at 3[V],the beam is thus snapped down at voltage beyond the pull-down voltage of 2.75[V].

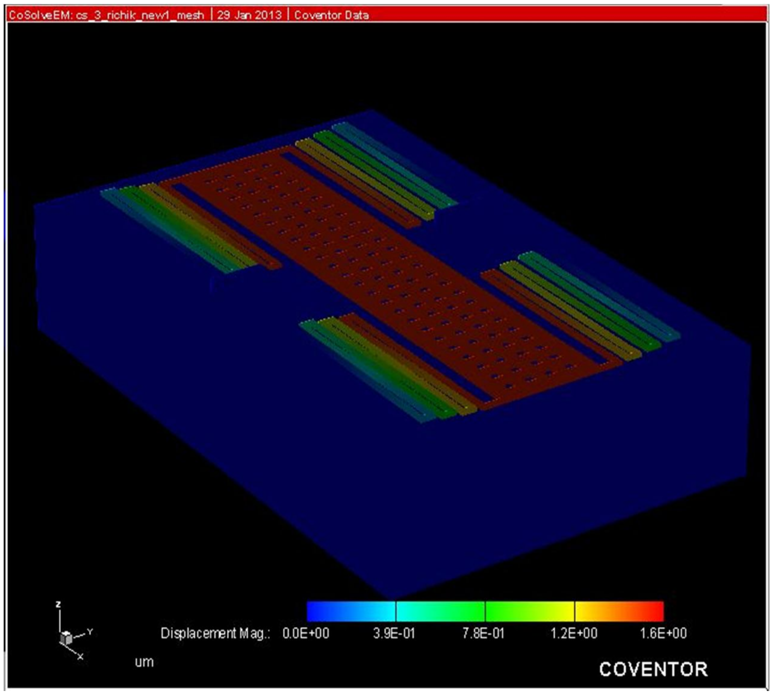

Fig.5: Displacement Magnitude surface plot of the beam.

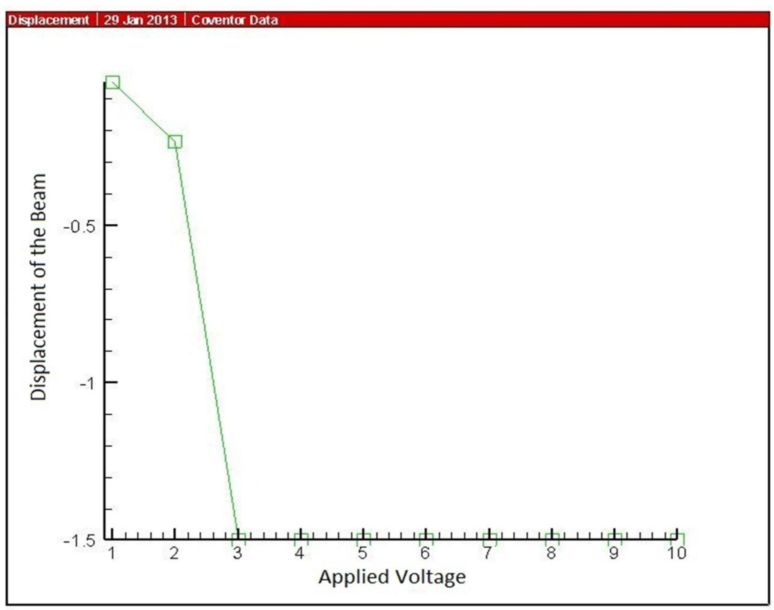

Fig.6: Displacement vs. Applied Voltage graph of the beam.

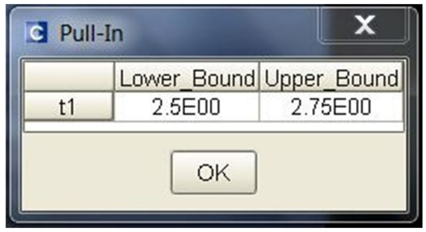

Fig.7: Lower Bound and Upper Bound limits for the Pull-in voltage.

5. Conclusion

A new compact architecture for the suspended mobile gate for a low-voltage SG-MOSFET is thus proposed. Maintaining an air-gap of 1.5µm is very rational from having a excellent isolation during 'off' state of the MOSFET. However, at such air-gap heights, the actuation voltage usually becomes high as the pull-in voltage is proportional to the 3/2th power of the initial air-gap,t_{gap0} . But the serpentine flexure hinge design for the suspended gate reduces its spring constant to about a value of 2.75[V] and also accounts for the compactness of the device, since no support structures are now present outside the MOSFET's substrate domain. With this design of the mobile gate, we could have a compact low-actuation voltage SG-MOSFET and also with an excellent isolation in the 'off' state.

References

A. N. Abele, R. Fritschi, K. Boucart, F. Casset, P. Ancey, and M. Ionescu, "Suspended-gate MOSFET: Bringing new MEMS functionality into solid-state MOS transistor," in *IEDM Tech. Dig.*, 2005, pp. 479–481.

[2] A. M. Ionescu, V. Pott, R. Fritschi, K. Banerjee, M. J. Declerq, P. Renaud, C. Hibert, P. Fluckiger, and G. A. Racine, "Modeling and design of a low-voltage SOI suspended-gate MOSFET (SG-MOSFET) with a metal over- gate architecture," in *Proc. ISQED*, 2002, pp. 496–501.

[3] Y. S. Chauhan, D. Tsamados, N. Abel´e, C. Eggimann, M. Declercqand A. M. Ionescu, "Compact Modeling of Suspended Gate FET", in 21st International Conference on VLSI Design, 2008 IEEE,pp.119-124.

[4] G. M. Rebeiz, RF MEMS: Theory, Design, and Technology. Hoboken, NJ: Wiley, 2003.

[5] Shimul Chandra Saha, Tajeshwar Sin&, Trond Saether, "Design and Simulation of RF MEMS Bridge Switches for High Switching Cantilever and Speed. and Low Voltage Operation and Their Comparison." in IEEE 2005,pp. 131-134.

[6] Abele N, Villaret A, Gangadharaiah A, Gabioud C, Ancey P, Ionescu A. M, (2006) 1T MEMS Memory Based on Suspended Gate MOSFET, Electron Devices Meeting, IEDM '06 International, San Francisco, CA. doi: 10.1109/IEDM.2006.346826.