Mechanical Model of RF MEMS Capacitor Structure

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Abstract: In order to design an RF MEMS based device, it is beneficial to have information concerning mechanical behavior. For model verification purpose, solution offered by simulation software equipped with predefined physics application is one valuable way to provide initial reference. When the number of elements involved in the equations is huge and more resources consumed accordingly due to thin multilayers, an approach to reduce number of elements is useful, though accuracy is one aspect that has to be taken into account.
Behavior of capacitor structures model shown throughout this study gives an opportunity to estimate the fabricated device and for which application it fits.

Keywords: RF MEMS capacitor, MEMS mechanical model

1. Introduction

MEMS (micro electrical mechanical system) structure is nowadays utilized in many aspects including in radio frequency field due to the fact that it enables the establishment of miniaturized and low power RF components.

Tunable or variable capacitor is required in a variety of RF applications such as filter, adjustable matching network, phase shifter and many more. An RF MEMS electrostatic tunable capacitor based on two parallel plates has been introduced for the last decades. Since then the research to enhance its tunability driven by a moderate actuation voltage in its operation and with low cost and simple fabrication takes place in academia as well as industries.

In order to realize such MEMS structure, it is important to have information concerning how pre-stressed structural elements deform after removal of sacrificial layer. By having this information, one can thoroughly calculate the initial distance between the two plates and furthermore estimate the existing capacitance, and also the actuation voltage applied necessarily on the plates to tune the capacitance. Moreover, the capacitance ratio can be analyzed whereas this would be an essential interest of particular RF applications.

2. Material and Design

Throughout this work the designed RF MEMS capacitor is based on two aluminum plates separated by dielectric layers and air gap as illustrated in Figure 1.

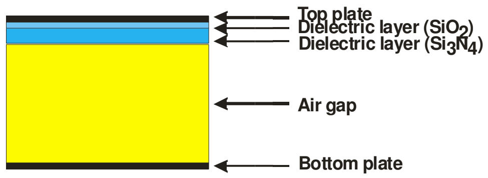

Figure 1. Cross section view of capacitor structure

Material of conductor plates used here is thin aluminum. In order to have an air gap, a so called sacrificial layer is deposited and removed at the end of the process. Dielectric layer is deposited using a plasma enhanced chemical vapour deposition (PECVD) and the influence of stress in dielectric is observed after the structure is released whereas the total stress determines whether the released structure is tensile or compressively strained. According to [1] among others, this influence can be compensated by introducing a compensation layer which brings the chance to minimize the unwanted strain effect. However, this compensation layer in some applications may contribute undesired influences as well, such as light phase shifting in optical MEMS. Hence, investigation reported in [2] shows the possibility to control the intrinsic stress of dielectric material by changing the duty cycle of plasma excitation frequencies when single dielectric layer is mandatory.

During the initial experiment, it is observed that SiO_2 single dielectric layer leads to a compressive strain on the produced structure and consequently, releasing sacrificial layer underneath to produce the air gap is not an easy task to carry out. Therefore, despite the facts mentioned before, a compensation Si_3N_4 dielectric layer is employed within this work since its disturbing effects are not the main concern. The Si_3N_4 dielectric layer is deposited before SiO_2 layer at 80^{o}C temperature and the sufficient strain is obtained when the thickness of Si_3N_4 layer is approximately 7 times the thickness of SiO_2 layer. The initial stress observed here is in the range of hundreds of MPa.

3. Structure model

Relationship among components of stress (σ) and shear stress (τ) on three dimensional x-y-z space is governed by force balance at static equilibrium condition. With volume force (K), the relationship is given as:

$$-\frac{\partial \sigma_x}{\partial x}-\frac{\partial \tau_{xy}}{\partial y}-\frac{\partial \tau_{zx}}{\partial z}=K_x$$
$$-\frac{\partial \tau_{xy}}{\partial x}-\frac{\partial \sigma_y}{\partial y}-\frac{\partial \tau_{yz}}{\partial z}=K_y$$
$$-\frac{\partial \tau_{zx}}{\partial x}-\frac{\partial \tau_{yz}}{\partial y}-\frac{\partial \sigma_z}{\partial z}=K_z$$

With *u*, *v*, *w* as deformation components, strain (ε_i) and shear strain (ε_{jk}) components are defined as:

$$\varepsilon_x=\frac{\partial u}{\partial x} \qquad \varepsilon_{xy}=\frac{\gamma_{xy}}{2}$$
$$\varepsilon_y=\frac{\partial v}{\partial y} \qquad \varepsilon_{yz}=\frac{\gamma_{yz}}{2}$$
$$\varepsilon_z=\frac{\partial w}{\partial z} \qquad \varepsilon_{xz}=\frac{\gamma_{xz}}{2}$$

According to the Hooke's law, the relationship between stresses (σ and τ) and strain (ε) in particular material is given by:

$$\sigma_x=\frac{E}{1+\nu}\left(\varepsilon_x+\frac{\nu}{1-2\nu}\left(\varepsilon_x+\varepsilon_y+\varepsilon_z\right)\right)$$
$$\sigma_y=\frac{E}{1+\nu}\left(\varepsilon_y+\frac{\nu}{1-2\nu}\left(\varepsilon_x+\varepsilon_y+\varepsilon_z\right)\right)$$
$$\sigma_z=\frac{E}{1+\nu}\left(\varepsilon_z+\frac{\nu}{1-2\nu}\left(\varepsilon_x+\varepsilon_y+\varepsilon_z\right)\right)$$
$$\tau_{xy}=\frac{1}{2}\left(\frac{E}{1+\nu}\right)\gamma_{xy}$$
$$\tau_{yz}=\frac{1}{2}\left(\frac{E}{1+\nu}\right)\gamma_{yz}$$
$$\tau_{zx}=\frac{1}{2}\left(\frac{E}{1+\nu}\right)\gamma_{zx}$$

where E is the Young's modulus, ν is the Poisson's ratio, and γ is shear strain.

When dealing with thin multilayers in simulation, one main problem is that the number of small elements built by simulator gets very huge and this conveys the fact that more complex calculations need to be solved. In order to cope with this, utilizing bulk model of multi layers could be one approach, as included in the work of [3]. Thus, in simulation a single bulk model is used and it represents multi dielectric layers with equivalent parameters. They are equivalent specific heat capacity (C_{eq}), equivalent density (ρ_{eq}), equivalent thermal conductivity (k_{eq}), equivalent Young's modulus (E_{eq}), equivalent Poisson's ratio (ν_{eq}), and equivalent thermal expansion coefficient (α_{eq}) as follows:

$$C_{eq}=\sum\frac{C_n x_n \rho_n}{x_n \rho_n}\ ; \quad \rho_{eq}=\sum\frac{x_n \rho_n}{x_n}$$
$$k_{eq}=\sum\frac{x_n k_n}{x_n}\ ; \quad E_{eq}=\sum\frac{A_n E_n}{A_n}$$
$$\nu_{eq}=\sum\frac{\nu_n x_n}{x_n}\ ; \quad \alpha_{eq}=\sum\frac{\alpha_n f_n E_n}{f_n E_n}$$

x_n and A_n are material thickness and cross section area of interest. Index n refers to each layer respectively.

Through this mechanical model study, one important aspect is to have information concerning the distance between the aluminum plates once the sacrificial layer is removed. This is obviously related to the electrical capacitance of the structure since the capacitance is basically a function of distance and area of conductors involved.

Another figure of merit of RF MEMS is to have low actuation voltages. As reported in [4], one method to reduce actuation voltage for such MEMS based capacitor structure is by introducing meander suspension beams. Such suspension determines the effective spring constant, which is proportional to the actuation voltage. Moreover, in [5] the investigation shows the relation between effective spring constant and the number of meander suspension sections applied.

Several structures with different type of suspension are modeled throughout this study. The center of all structures, which is designed to function as a membrane, is maintained to be a square with 70 µm length. As shown in Figure 2(a), the first structure includes a membrane supported by two suspensions. The next structure, given in Figure 2(b), consists of a membrane with two meander suspensions. In Figure 2(c) a membrane sustained by four meander suspensions is shown. Predefined physics application provided by state of the art mechanics simulation tool is carried out to solve the equations throughout these models [6].

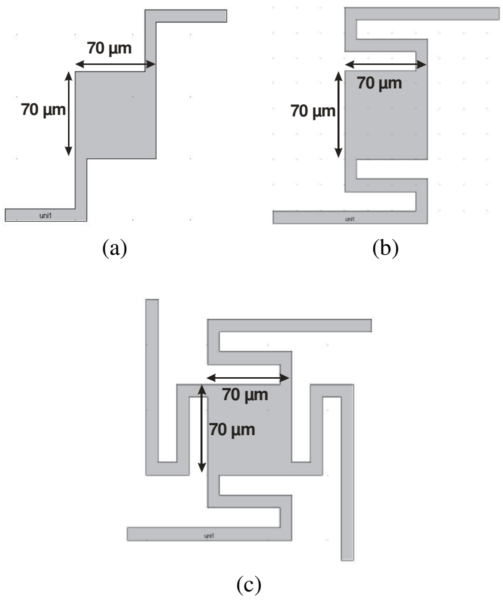

Figure 2. Top view of first structure (a), second structure (b), and third structure (c)

4. Results and Conclusion

The simulation results shown in Figure 3, Figure 4, and Figure 5 provide distinguished information about the behavior of each structure. It can be seen that the structures show sufficient tensile strain as the result of additional Si_3N_4 compensation layer other than SiO_2 dielectric layer. As far as the effective membrane area is sufficient, such concave shape is beneficial particularly when considering the effort to remove the sacrificial layer.

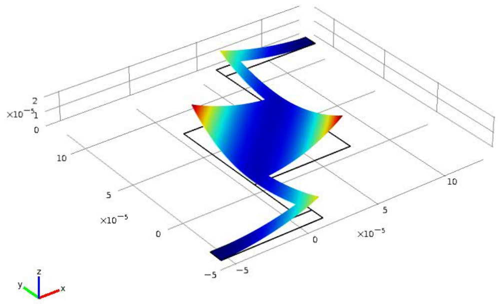

Figure 3. Simulation result for the first structure.

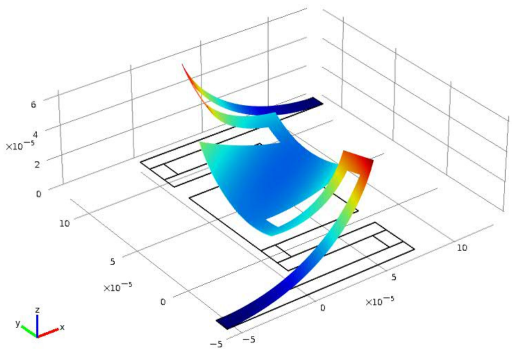

Figure 4. Simulation result for the second structure

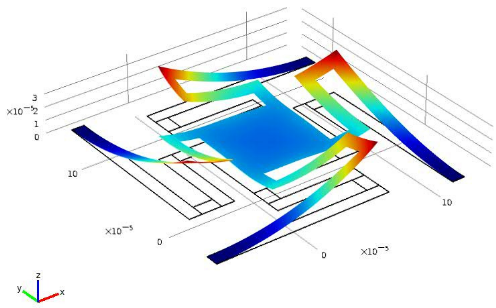

Figure 5. Simulation result for the third structure

Compared to the other two results, result for the third structure shows the highest effective membrane area. On the other hand, result for the second structure demonstrates the highest gap between the two conductor plates. For capacitor purpose, effective area and distance between plates play an important role. The second structure, for instance, is suitable for an application requiring small capacitance.

8. References

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9. Acknowledgements

This work is funded by ZFF Program of the University of Kassel. Institute of Nanostructure Technologies and Analytics of the University of Kasel is gratefully acknowledged for providing facility to perform this study.