MEMS Electrostatically Actuated Resonators

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***Abstract*— A MEMS electrostatically actuated resonator with fixed-fixed and fixed-free cantilever beams is designed, simulated, fabricated, and tested. The fabrication of the MEMS resonators uses RIT's MEMS fabrication 2016 process flow which is a surface micromachining process. The released fixed-free devices tested showed an increasing change in capacitance with an increasing actuation voltage. Inspection of the released fixed-fixed devices has a compressive stress in the second polysilicon film that causes the cantilever beam to bend above the actuation and sensing pads. Testing for resonance has not been successful. Some new considerations for the MEMS fabrication process and design are discussed.**

Keywords: MEMS, Resonator, surface micromachining process

I. Introduction

MEMS resonators are used instead of traditional LC filters or quartz resonators because of their small size, low power consumption, high q factor, improved reliability, and performance, and being able to integrate them into a CMOS process. The electrostatically actuated MEMS resonator uses a cantilever beam to oscillate with a resonant frequency that can be used to filter out signals that are not at the resonant frequency, integrated timing within semiconductor circuits or for mass sensing.

II. Theory

The resonator uses a cantilever beam that will oscillate at a resonant frequency which is based on the material properties and cantilever dimensions. Young's modulus is a measure of elasticity, equal to the ratio of the stress acting on a material to the strain that is produced. Young's Modulus for Silicon used in the design calculations of the resonators is 1.9E11 N/m^2. A clamped-clamped or fixed-fixed cantilever beam is anchored on both ends so that they do not move as shown in Figure 1. [4]

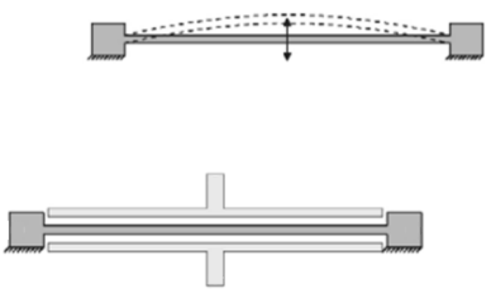

Figure 1: An example of a Fixed-Fixed cantilever (top view).

A clamped-free or fixed-free cantilever beam is anchored on one end and the other end of the beam can move as shown in Figure 2. The moment of inertia for the both types of cantilever beams is $I=bh^3/12$ where b is the beam width and h is the beam height. The resonant frequency for a fixed-fixed cantilever is determined by (1) and the resonant frequency for a fixed-free cantilever is (2) where E is Young's Modulus for silicon, I is the moment of inertia, and L is the beam length. [3]

$$f_o = (1/2\pi)(22.373/L^2)\sqrt{(EI/\rho)} \quad (1)$$

$$f_o = (1/2\pi)(3.5156\ /L^2)\sqrt{(EI/\rho)} \quad (2)$$

The maximum cantilever beam deflection for both types is calculated by (3) where F is the electrostatic force of attraction being applied to the cantilever beam. [1]

$$Ymax = (FL^3)/(48EI) \quad (3)$$

To determine the electrostatic force being applied (4) is used where A is the area of the electrostatic pad, V is the voltage being applied, and d is the distance between the cantilever beam and the electrostatic pad and εo is the permittivity of free space (8.85E-14 V/cm) and εr is the relative permittivity of air(1.0). The capacitance between the cantilever beam and an actuator or sensing pads is calculated using (5). Finite element analysis is performed using Solidworks to verify calculations that were used for the design of the resonators. [1]

$$F= (\varepsilon o*\varepsilon r*A*V^2)/(2*d^2) \quad (4)$$

$$C = \varepsilon o*\varepsilon r*A/d \quad (5)$$

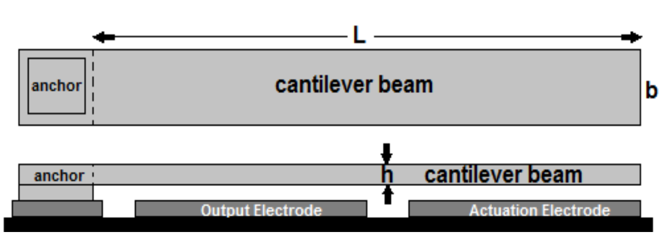

Figure 2: An example of a Fixed-Free cantilever (side view)[4]

III. Experiment

Design of the resonators was performed using Pyxis layout with variations in beam dimensions, actuation and sensing electrode location, and release. The variations in release are for the narrow fixed-fixed beams with and without holes and the area by which the release etch is done through to minimize the etch of the TEOS under the electrodes and to minimize the beams from breaking off during the entire release process. Figure 3 is an example of the Pyxis layout for a Fixed-Fixed cantilever. The cantilever beam is 20um wide with a 2um gap between the actuation electrode and the beam. Figure 4 is an example of the Pyxis layout for a Fixed-Free cantilever. The holes in the cantilever are designed 3um in diameter and spaced out by 15um.

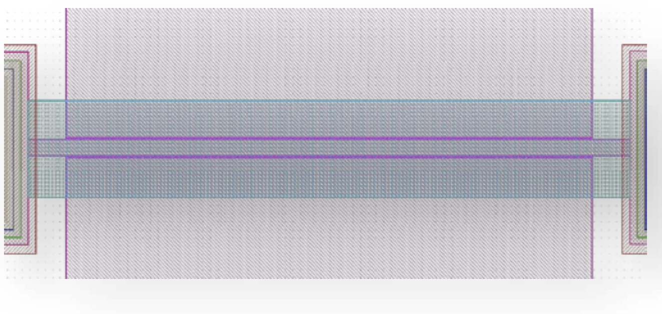

Figure 3: Fixed-Fixed Resonator using Pyxis layout.

Fabrication of the MEMS devices uses RIT 2016 MEMS fabrication process which is a surface micromachining process involving roughly 51 steps that include 8 levels of lithography shown in Figure X with a view of the thin film layers illustrated in Figure 5. The process begins with the ASML alignment marks being patterned and etched. A 6500A oxide is grown over the wafer on which the devices will be built upon. The first level of polysilicon is deposited and implanted. The features of poly1 are then patterned using Level 1 photolithography and plasma etched. A capping layer of 700A dry oxide is grown and then 4000A of nitride is deposited. Anchors to connect poly1 and poly2 are then patterned using Level 2 photolithography onto poly1 and the nitride and oxide is etched. A sacrificial layer of 1.75um thick TEOS is then deposited. The sacrificial oxide layer is defined with Level 3 photolithography and the rest is wet etched away in 10:1 BOE.

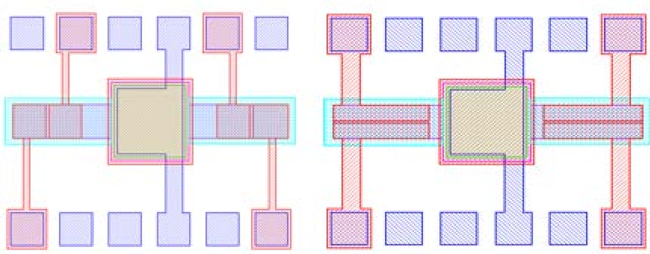

Figure 4: Fixed-Free Resonator using Pyxis layout.

The second level of polysilicon is deposited for a thickness of 2um. The No implant areas are defined in the fourth level of lithography and poly2 is implanted with P31 for 2E16cm-3 100KeV. A 500A pad oxide is grown and then 2000A of nitride is deposited. The Poly2 features are patterned using Level 5 photolithography and then the nitride, oxide and polysilicon is etched. The release holes are defined in the poly2 beams by which TEOS will be etch thru. Contact cuts for aluminum onto poly1 and poly2 are patterned using level 6 photolithography and the nitride and oxide is etched. Aluminum is sputtered, patterned in the level 7 photolithography and then etched. Finally, the devices are released by patterning level 8 photolithography and etching the TEOS around and through the poly2 features using 10:1 BOE with surfactant for 4 hours.

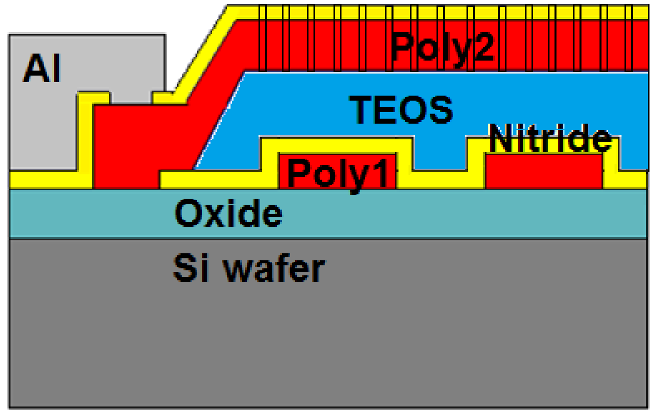

Figure 5: Side view of the thin film layers from the MEMS process flow for a MEMS Fixed-Free cantilever.

Actuation of the cantilever beam is accomplished by grounding the anchor which grounds the cantilever beam and applying a DC voltage to the actuation pad. A change in capacitance is sensed using a LRC meter between the cantilever beam and an output electrode. Resonant testing of the devices was tried using a DC bias voltage on the cantilever beam, an AC voltage on the actuation electrode using a frequency analyzer and the output of the sensing electrode connected to the input of the frequency analyzer

IV. RESULTS AND DISCUSSION

The finite element analysis of the cantilever beams was accomplished using Solidworks. Figure 6 illustrates a 1000umx20umx2um Fixed-Fixed cantilever beam modeled with both ends anchored and a 1uN of force applied to the side of the beam where the actuation electrode. When a calculated 23V is applied, it will create 1uN of force for a calculated maximum beam deflection of 0.87um. Solidworks predicted a 0.1um of maximum beam deflection and the difference between the simulation and the calculations used is within the same order of magnitude showing that the equations used adequate for design.

Fixed-Free finite element analysis of the cantilever beam is illustrated in Figure 7 with dimensions of 300umx100umx2um is modeled in Solidworks with one end anchored and a 1uN of force applied to the side of the beam where the actuation electrode would be. When a calculated 10V is applied, it will create 1uN of force for a calculated maximum beam deflection of 0.76um. The finite element analysis using Solidworks predicted a 0.43um of maximum beam deflection. The difference between the simulation and the calculations used is within the same order of magnitude showing that the equations used adequate for design.

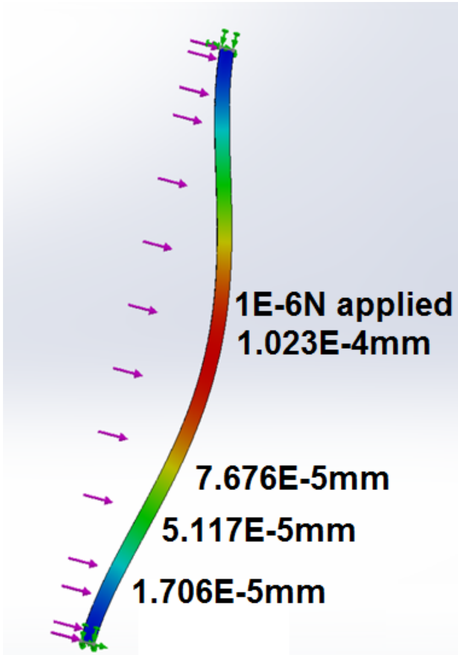

Figure 6: Fixed-Fixed cantilever beam in Solidworks with 1uN of force applied to the side.

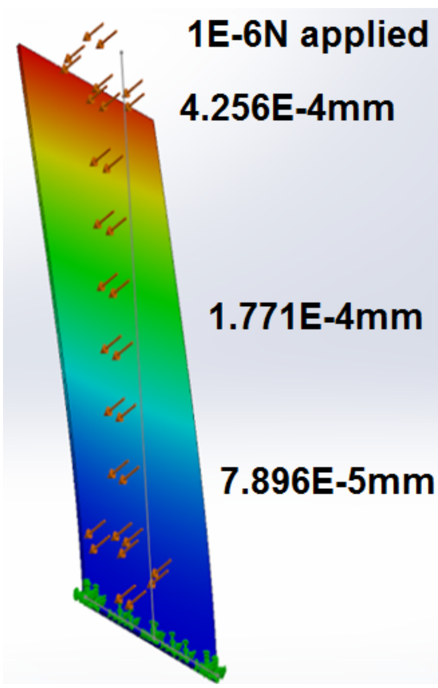

Figure 7: Fixed-Free cantilever beam in Solidworks with 1uN of force applied to the top.

Demonstration of the released cantilever beams was verified with a measured change in capacitance versus increasing electrostatic actuation voltage. The devices in Figure 8 are of the same size and type cantilever which were tested across the wafer showing the differences in actuation. Calculated actuation for this beam was 10v and tested actuation was between 10 to 25V. The fixed-free cantilever beam can be observed under the microscope to be deflecting which is shown in Figure 8. The picture in Figure 9 shows a top down view of the cantilever beam and the differences that are seen when no voltage is applied and the beam is up versus when voltage is applied and the beam is pulled down. Most of the released fixed-free devices show actuation but resonance testing of the devices has not been successfully completed possibly due to the high noise to signal in the test setup.

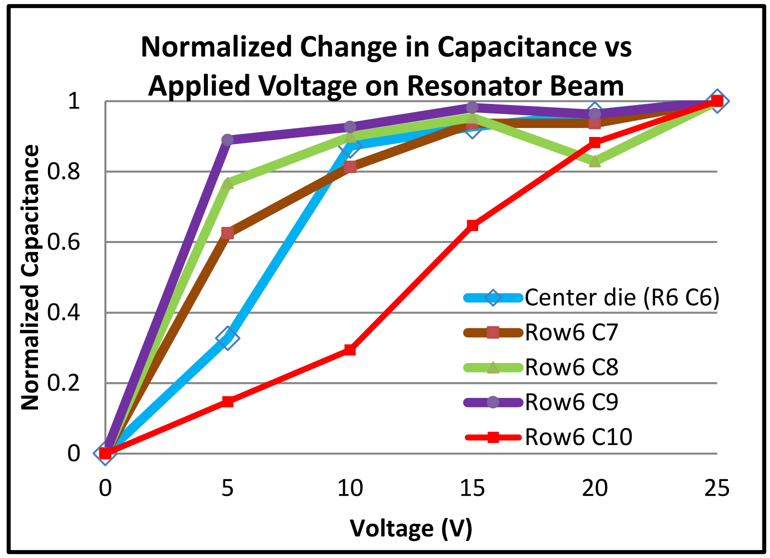

Figure 8: A graph of normalized capacitance versus voltage being applied to electrode.

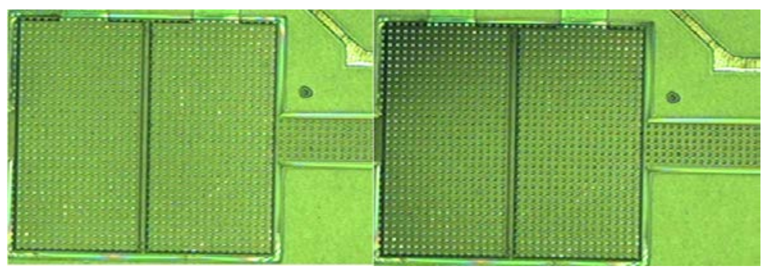

Figure 9: A picture of the cantilever beams with and without DC voltage being applied.

Release of the Fixed-Fixed cantilever beams showed a compressive stress in the polysilicon film from deposition and was not discovered until after release of the MEMS devices. Figure 10 shows the cantilever beam out of focus from the actuation and sensing electrodes. Figure 11 is an illustration of the compressive stress observed in the polysilicon film and how the cantilever beam does not line up with the actuation and sensing pad. There has been no successful actuation of fixed-fixed beams due to small area of actuation are between the beam and pad. Further investigation will be needed into the deposition of the poly2 layer to minimize film stress or a redesign of the cantilever beam possibly with some springs or the cantilever not being anchors on one side to reduce or eliminate the stress. Some new considerations for the MEMS fabrication process and design are a larger contact cut area in order for better end point detection during the plasma etch of the nitride instead of doing a timed etch. An investigation into the deposition recipe for polysilicon in order reduce or eliminate the stress in the film. Another observation is that hole placement in design matters. Release holes in locations that have a large change in steps heights in film thickness like right at the anchor of the beam and where the TEOS overlap otherwise the photolithography of the holes will be out of focus and change in size from design.

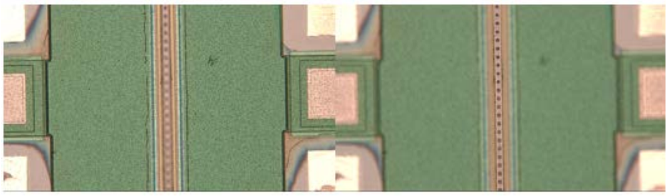

Figure 10: A picture of the fixed-fixed cantilever beam out of focus from the electrodes.

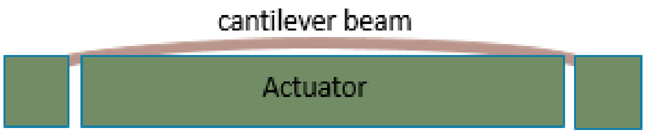

Figure 11: Side view illustration of the compressive stress observed in Poly2.

V. Conclusions

MEMS cantilever resonators were designed, simulated, fabricated, and tested for this project. The two types of cantilever designs were fixed-fixed and fixed-free with variations in beam dimensions, actuation and sensing pad design, cantilever beams with and without release holes. Simulations using Solidworks confirmed the equations and calculations that were used for design within an order of magnitude. Fabrication of the MEMS devices was done using a surface micromachining process of 50 steps and 8 photolithography layers. Successful release of the devices showed actuation with an increase in capacitance with increasing voltage as well as visible deflection. Testing for resonance has not been successful. Some considerations for the MEMS fabrication process and design were proposed.

VI. Future Work

Future improvements would be in the frequency testing of the resonators or to integrate a pre-amplification circuit onto the circuit to increase the signal to noise ratio. Another approach to use the resonators would be in a biomass sensing application that would change the resonate frequency or to use the resonator in a CMOS process for circuit timing. Investigation of the stress in the polysilicon film or a redesign of the cantilever to reduce or eliminate the stress.

Appendix

1. Starting wafer
2. PH03 – **level 0**, Marks
3. ET29 – Zero Etch
4. ID01-Scribe Wafer ID, D1…
5. ET07 – Resist Strip, Recipe FF
6. CL01 – RCA clean
7. OX04 – 6500Å Oxide Tube 1
8. CV01 – LPCVD Poly 5000Å
9. IM01 – Implant P31, 2E16, 60KeV
10. PH03 – **level 1** Poly-1
11. ET08 – Poly Etch
12. ET07 – Resist Strip, Recipe FF
13. CL01- RCA Clean
14. OX05 – 700Å Dry Oxide
15. CV02- LPCVD Nitride 4000Å
16. PH03 – **level 2** Anchor
17. ET29 – Etch Nitride
18. ET07 - Resist Strip, Recipe FF
19. CL01 – RCA Clean
20. CV03-TEOS SacOx Dep 1.75um
21. PH03 – **level 3** SacOx Define
22. ET06 - wet etch SacOx Define Etch
23. ET07- Resist Strip, Recipe FF
24. CL01 – RCA Clean
25. CV01-LPCVD Poly 2um, 140 min
26. PH03 - **level 4** No Implant
27. IM01-P31 2E16 100KeV
28. ET07 Resist Strip, Recipe FF
29. CL01 – RCA Clean
30. OX05- 500Å pad oxide
31. CV02 – 2000Å nitride
32. PH03 - **level 5** Poly2
33. ET29 – Plasma Etch Nitride
34. ET06 – Wet Etch pad oxide
35. ET68 - STS Etch Poly2
36. ET07 - Resist Strip, Recipe FF
37. PH03 – **level 6** Contact Cut
38. ET29 – Etch Nitride Contact Cut
39. ET06 – Etch Oxide Contact Cut
40. ET07 – Resist Strip, Recipe FF
41. CL01 – RCA Clean two HF
42. ME01 – Metal Deposition - Al
43. PH03 – **level 7** Metal
44. ET55 – Metal Etch - wet
45. ET07 – Resist Strip
46. PH03 – **level 8** – Release
47. SA01 – Saw wafers ½ Thru
48. ET66 – Final SacOx Etch
49. ET07 - Resist Strip, Recipe FF
50. SEM1 – Pictures
51. TE01 - Testing

Figure 12: RIT's 2016 MEMS Fabrication process flow. [2]

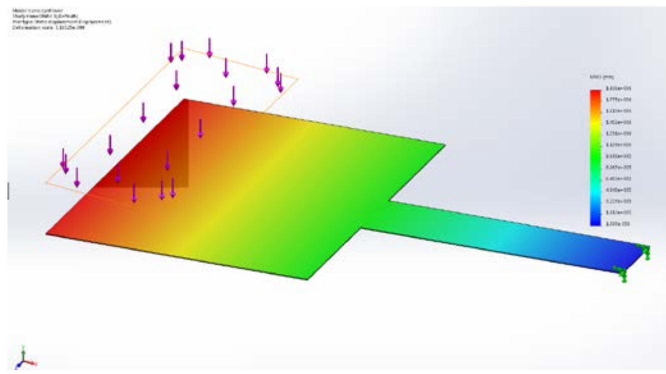

Figure 13: Another Solidworks simulation of a fixed-free cantilever.

Acknowledgment

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[2] "L. Fuller." (2016): *SurfaceMEMSFabricationDetails*. RIT, 1 Nov. 2016. Web.

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[4] R. M. C. Mestrom, R. H. B. Fey, J. T. M. van Beek, K. L. Phan, and H. Nijmeijer, "Modelling the dynamics of a MEMS resonator: Simulations and experiments," Sensors and Actuators a-Physical, vol. 142, pp. 306-315, Mar 2008.