MULTI-CAVITIES MEMS CAPACITIVE PLATES FOR POWER HARVESTING

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Abstract: 2×2 mm^2 MEMS capacitive plates with two cavities (two capacitors) have been designed, modeled and fabricated for power harvesting by utilizing unwanted mechanical vibration in environment using electrostatic mechanism. The device is unique in the use of an innovative two-cavity design, and the use of electroplated nickel as the main structural material. When the capacitance increases for one capacitor, it will decrease for the other. This allows us to use both capacitors to optimize the efficiency of power harvesting. Dynamics models are established using "Matlab" for different combination of forcing frequencies and vibration amplitude and accordingly average current and power are computed. The prototype of MEMS capacitive plates have been successfully fabricated, the initial testing has been implemented.

Keywords: Multi-cavities, capacitive MEMS plates, power harvesting.

INTRODUCTION

The electrostatic capacitive plates for power harvesting using various designs have been studied in recent years. These include a multi-gap comb fingers microstructure and suspended proof mass within a frame above the substrate for energy scavenging and voltage step-up conversion. The existing work related to variable parallel plate capacitor was more focused on comparatively macro and single cavity model. In our work, we designed and fabricated micro-machined MEMS capacitive plates for voltage conversion and power harvesting application with novel design of two cavities which lead to two simultaneous variable capacitors. In this paper, the design and operational principle of the MEMS capacitive plates will be explained. Dynamic analysis of the outputs of the MEMS capacitive plates using "Matlab" will be addressed. The fabrication process has been developed and optimized. Initial tests have been implemented to confirm the successful suspension of the movable plate and its mechanical property.

DESIGN AND PRINCIPLE OF OPERATION

The MEMS capacitor (See Fig. 1) consists of two capacitive cavities, with serpentine shape suspension beams, and fixed plates patterned with Chrome and Gold thin films. Five stoppers on the fixed plates were formed by electroplated gold to prevent snap-down of the movable plates. Two thin layers of silicon nitride and silicon dioxide were deposited on fixed plates to enhance the dielectric property of the capacitors. The charge control strategy [1, 2] of the MEMS capacitive plates is uniquely suitable for power harvesting applications as the following: The capacitive plates are charged by a low voltage source when the gap of the parallel plates starts decreasing. The capacitance increase causes the capacitor to take in more charge. When charging stops, the plates try to bounce back to higher position so that the capacitor gap increases. Consequently, the capacitance decreases and the

voltage increase because the total charge is conserved. Discharge starts when the voltage reaches a preset higher value. The above sequence repeats to achieve continuous power harvesting.
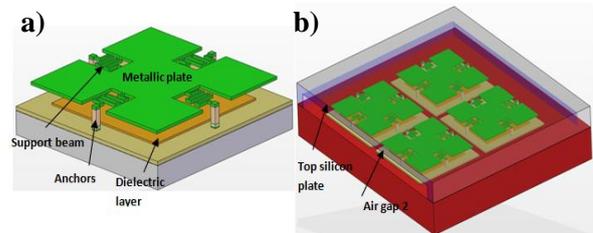

Fig. 1: The 3-D view of 2mm×2mm MEMS capacitive plates' geometries, a) single device without the 2nd capacitive cavity, b) array devices with the top plate and two capacitive cavities.

MODELING

The initial dynamic model was created based on conventional design of electrostatic power scavenger with single cavity. The movable plate is supported by four serpentine springs. Four stopper springs are placed on fixed plate to avoid short circuit during the collision of movable plate with fixed one. The schematic of electric control is shown in Fig. 2b. Output battery voltage is more than input power source. Charge across the plates is controlled by diodes. The whole arrangement is placed on a base to which vibration force is applied.

We assume that the package containing the capacitors is subject to sinusoidal displacement given by:

$$y(t) = b \cos \omega t \qquad (1)$$

Therefore, the equation of motion for the plate is given by the following equation:

$$m\ddot{d}_1 = -c\dot{d}_1 - k(d_1 - d_0) + f_i - f_e \qquad (2)$$

where d_1 is the gap between the two plates, m the mass of the moving plate, and k the stiffness of the elastic support. The coefficient c accounts for the damping, mainly from the squeezed air film in the gap of the
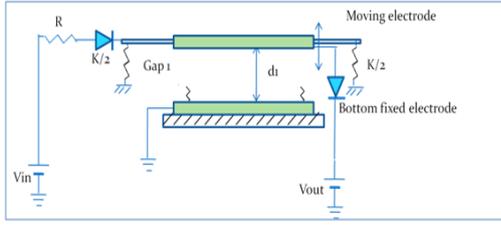
capacitive plates.

Fig. 2: Model of conventinal single cavity power scavenger, arrangement of stoppers, springs, and electric control.

The term f_i represents the inertia force if the device is subjected to base excitation. For displacement given by (1), we have:

$$f_i = mb\omega^2 \cos \omega t \qquad (3)$$

The term f_e represents the electrostatic force due to the charge on the plate. Our two-air-cavity design has two capacitors sharing a common electrode. The electrostatic force is the sum of the two. Through charging and discharging, the capacitive plates exchange energy with the electrical components both upstream and downstream, mechanical energy is dispensed in the process. If the device is sealed in a vacuum, the mechanical damping can be negligible. The electrostatic force f_e refers to the electrostatic force over two capacitive plates. The plate capacitance is given by:

$$C = \frac{\varepsilon A}{d} \qquad (4)$$

where ε is electrical permittivity, A is the plate area, and d is the plate separation. For plates with varying gap, the electrostatic force caused by a voltage difference is:

$$f_e = -\frac{\varepsilon A V_c^2}{2d^2} \qquad (5)$$

Since the gap is varying, this force is dependent on the plate displacement. When the gap decreases, the electrostatic force increases. This force is nonlinear which means the increase is not proportional to the displacement. The increase may overwhelm the restoring force of the elastic support to cause the gap to collapse. When this is caused by the gradual increase of the voltage, a critical voltage, called the pull down voltage, is known to exist:

$$V_{pd} = \sqrt{\frac{8kd_0^2}{27C_0}} \qquad (6)$$

where d_0 and C_0 are the gap and capacitance at static equilibrium when no voltage is applied. The electrostatic force is determined by the voltage on the capacitor. The voltage is calculated from the charge on the plate:

$$V_c = \frac{Q}{C} \qquad (7)$$

The charge on the plate can be determined by keeping track of the current flowing in and out the capacitor. However, since the plate capacitance is very small, charging and discharging time is very short. Keeping track of the current flow would require additional differential equation. The numerical solution of this additional equation would require extremely small integration time steps to prevent numerical instability. Since the short charging and discharging time can be ignored, we assume that the charge on the plate is constant when no charging or discharging takes place. That is, Q is constant if $V_{in} < V_c < V_{out}$. By ignoring the charging and discharging time, we set up the following limitations on the voltage on the capacitor: $\min V_c = V_{in}$ and $\max V_c = V_{out}$. The above limitations are imposed at the end of each time integration step. If the voltage exceeds V_{out}, we calculate the excess electric charge which is moved to the battery V_{out}. If the voltage is below V_{in}, V_c is reset to V_{in}. To avoid the collision between the plates, we placed four stoppers on the fixed plate. The moving plate makes contact with the stopper when its displacement is 80% of the initial gap. The stopper is modeled as a very stiff spring whose spring constant is 1000 times of the plate suspension. Therefore, the stopper acts like a nonlinear spring and its force can be written as in the following:

$$F_{ns} = 1000k \max(-(d_1 - d_0) + 0.8d_0, 0) \qquad (8)$$

The damping coefficient c represents the loss of energy associated with the plate motion; the damping by the air surrounding the plate is the main contributor to the damping. We introduce the damping ratio ζ, in the following:

$$\zeta = \frac{c}{2\sqrt{mk}} \qquad (9)$$

Introduce the dimensionless displacement as in the following: $d_1 = d_0(1+x)$. We obtain the following equation of motion:

$$\ddot{x} = -2\zeta\omega_0\dot{x} - \omega_0^2 x + \frac{1}{md_0}(-F_e + F_i + F_{ns}) \qquad (10)$$

For single cavity model, movable plate will move up and down and after some time it will start striking on stopper spring at bottom only. It does not have any limit in up direction. For low forcing frequency and amplitude of vibration, moving plate will stick to bottom plate stoppers because of pull down voltage and stays there only which results in no stepping up of voltage. Using the equations of forces for movable plate we developed Matlab program to simulate the one cavity system. The model of the MEMS capacitive plates with two cavities was similarly established which consists of two variable capacitors with gap1 and gap2 (Fig. 3). Force acting on movable plate of two cavities model is similar to one cavity model but one additional electrostatic force F_{e2} is introduced due to second cavity capacitor.
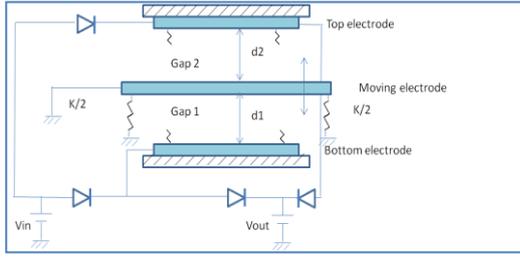
Fig. 3: Arrangement of electric control of two cavities model.

So the equation for two cavities system becomes:

$$\ddot{x} = -2\varsigma\omega_0\dot{x} - \omega_0^2 x + \frac{1}{md_0}(F_{e2} - F_{e1} + F_i + F_{ns}) \quad (11)$$

In two cavity model, stopper springs are placed on both fixed plate electrodes. So as voltage reaches to pull down voltage, the moving plate starts striking on stopper springs. At low forcing frequency and amplitude of vibration plate will stick either at upper or at bottom fixed plate stopper because of pull-down voltage. Using the equations of forces for movable plate of two cavities model, we similarly developed Matlab program to simulate the two cavity system. The specifications used for Matlab simulation are as following: area of plate = 2 mm $\times$ 2 mm, thickness of plate= 10 μm, specific density of Nickel material = 8912 kg/m^3, gap between two plates 30 μm, pull-down voltage = 20V, input Voltage = 15V, and downstream voltage = 45V.

Table 1: Average Power (Average Current $\times$ Output Voltage) for Single Cavity Model.

Forcing frequency= X × natural frequency	0	0.5	1	1.5	2	2.5	3	3.5
Amplitude								
250	0	0	9.5E-07	3.42E-07	1.15E-06	1.17E-06	1.14E-06	1.13E-06
200	0	0	2.42E-07	4.15E-07	1.14E-06	1.16E-06	1.13E-06	1.12E-06
150	0	0	0	5.65E-07	1.12E-06	1.15E-06	1.14E-06	1.06E-06
100	0	0	0	4.65E-07	1.08E-06	1.13E-06	1.13E-06	8.42E-07
50	0	0	0	0	0	1.01E-06	1.09E-06	1.04E-06
0	0	0	0	0	0	0	0	0

Table 2: Average Power (Average Current $\times$ Output Voltage) for Two Cavity Model.

Forcing frequency= X × natural frequency	0	0.5	1	1.5	2	2.5	3	3.5
Amplitude								
250	0	0	7.77E-07	1.96E-06	4.14E-06	5.54E-06	8.22E-06	1.32E-05
200	0	0	0	1.57E-06	2.95E-06	4.66E-06	6.98E-06	1.06E-05
150	0	0	0	1.36E-06	2.32E-06	4.3E-06	5.33E-06	8.02E-06
100	0	0	0	1.12E-06	1.8E-06	3.04E-06	4.72E-06	5.67E-06
50	0	0	0	0	1.37E-06	2E-06	2.94E-06	3.78E-06
0	0	0	0	0	0	0	0	0

Using Matlab programs for simulation, average power for single cavity and two cavity models are computed (table 1 and table 2). Single cavity model gives 1.17 microwatt of power and for two cavity model we get 13.2 microwatt of power, which concludes that two cavity model gives better results compare to single cavity model. Also as we increase amplitude or forcing frequency, generally average power increases, some exceptions are also observed.

FABRICATION

The MEMS capacitive plates with multiple cavities were first fabricated on top of silicon substrate using surface micromachining. Fig.4 shows cross-sections of the fabrication processes.
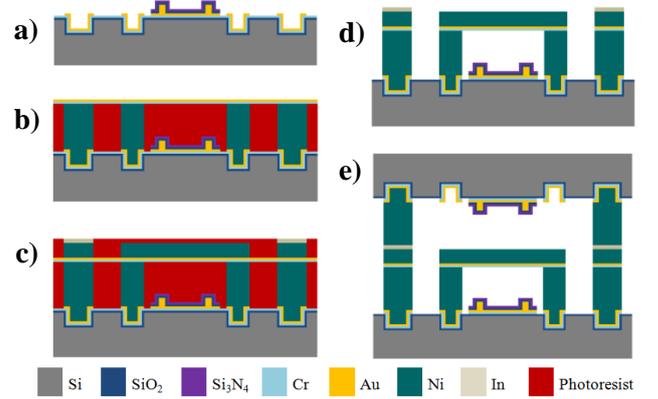

Fig.4: Fabrication flow cross section schematics of the Multi-Cavities MEMS capacitive plates.

The fabrication processes starts with etching 3 μm deep rectangular trenches into a silicon wafer at location corresponding to the anchors of capacitive plates and bonding pads using Reactive Ion Etching (RIE). The patterned wafers were then thermally oxidized to grow SiO$_2$ layer for insulation. Thin layers of Cr and Au were sputtering deposited. Cr serves as an adhesion layer for Au. The Au layer was patterned to form the bottom plates, bottom and top electrodes, trace lines, and the seed layer at location corresponding to the capacitor anchors and bonding pads. Another Au was electroplated inside of a photoresist mold to create stoppers. Thin layers of SiO$_2$ and Si$_3$N$_4$ were then sputter deposited and patterned to the shape of bottom plate to enhance the dielectric property of the capacitors (Fig. 4a). A thick photoresist sacrificial layer was patterned with a height of 30 μm serving as mold of capacitor anchors and bonding pads. Ni was electroplated inside of the mold for forming capacitor anchors and bonding pads. The second seed layer of Cr and Au was similarly sputtering deposited (Fig. 4b). A photoresist mold was patterned on top of seed layer for creating the top movable plate with serpentine shape suspension beams. The Ni was electroplated inside of the photoresist mold for 10 μm thick. One more photoresist mold defining bonding pads was pattern on top of the previous mold for electroplating 1 μm thickness of In for bonding purpose (Fig. 4c).

Finally, the two Photoresist molds on top of the second seed layer were removed by flushing with acetone and 2-Isopropanol and DI water very carefully without attacking the sacrificial layer. The second seed layer was removed by etching Au and Cr. The sacrificial layer was released in hot photoresist stripper bath. The ultrasonic agitation was added to help removal of the photoresist between the top and bottom plates. The Cr layer on the bottom substrate serving as

first seed layer was finally etched (Fig. 4d). The bonding process was completed by aligning another substrate with only fixed plate and 30 µm height of bonding pads to the substrate with movable plate using hotplate. The substrate with movable plate and In bonding layer was heated at 200C, two substrate was bonded when the In bonding layer was melt (Fig. 4e).
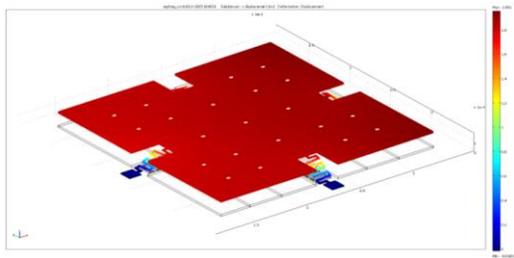
RESULTS

Fig. 5: 3D FEM simulation of vibration of single MEMS capacitive plate, natural frequency was found to be 2815Hz.
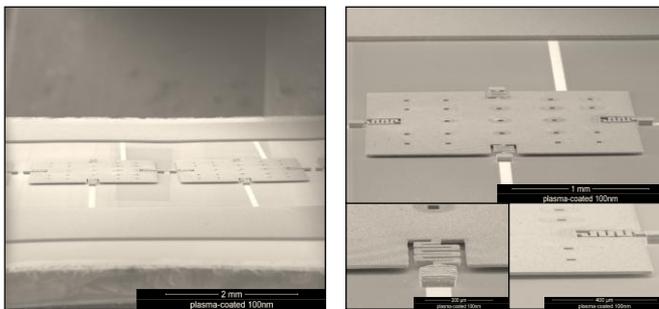
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Fig. 6: SEMs of MEMS capacitive plates without bonding the second cavity.

Finite element modeling (FEM) of the designed MEMS capacitive plates was implemented in CONSOL Multi-Physics finite element tool for analyzing the mechanical property of designed structure. The 3D FEM model according to MEMS capacitive plate's geometries is shown in Fig. 7. The natural frequency of the structure was found to be 2815Hz, the corresponding spring constant of the structure is 1100N/m. It is observed that the movable plate deflects with uniform bending, and the corresponding pull- down voltage was determined to be 31.9V.

Scanning Electron Microscope micrographs (SEMs) of the fabricated MEMS capacitive plates are shown in Fig. 5 and Fig. 6. Initial tests were performed to confirm the successful suspensions of the electroplated nickel plates. This is achieved by measuring the change of capacitance with increasing applied voltage on a single cavity design. The pull down effect was observed at around 30V (Fig. 8), which verifies the FEM modeling results. The devices are then bonded to vibration stage for excitation with various frequency and amplitude by using external power extraction circuit, and charged with by applying

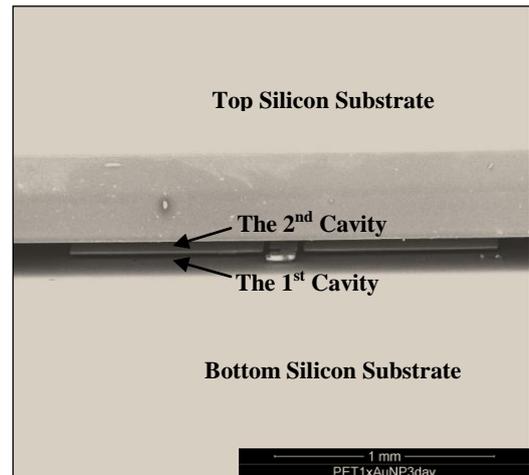5 volt. The power gain under different vibration conditions will be reported in a future paper.

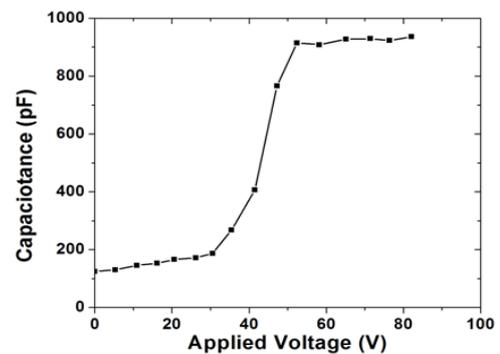*Fig. 7: SEMs of 2mm×2mm MEMS capacitive plate with two-cavities.*

Fig. 8: Curve shows the change of capacitance with increasing applied voltage, pull-down effect is observed at around 30V.

CONCLUSION

The fabrication processes for each layer forming the Multi-cavities MEMS capacitive plate were optimized, and the initial prototypes were successfully fabricated. We have identified the ranges of the forcing frequencies and amplitudes for which power generation on the order of µwatts is achieved. By tracking the change of the electric charges on the capacitors, we are able to compute the current, hence the power that can be achieved by the power harvester. We now have a numerical program that can calculate the harvested power for given geometric design and for given vibration amplitude and frequencies.

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