ELECTROSTATIC MICRO POWER SCAVENGER WITH DUAL CAVITIES

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Abstract: We have designed, modeled, fabricated and tested a novel 2×2 mm^2 MEMS electrostatic power scavenger with dual capacitive cavities for vibration to electric energy harvesting. The device is unique in the use of a dual-cavity design and electroplated nickel as main structural material. When the capacitance increases for one cavity, it decreases for the other. This allows using both up and down directions to generate energy. Comprehensive dynamic simulations of the devices were performed using Matlab, which assuming the movable plate is allowed to have translational degree of freedom with rocking instability. The devices have been successfully fabricated using surface micromachining and experimentally characterized using a PCB test board mounted on a shaker and a NI USB-6218 DAQ controlled by Labview. The resonance of the device was observed around 500 Hz. A maximum power of 225 nW was achieved under a high DC bias of 15 V and intense excitation above 5 g.

Keywords: Electrostatic, MEMS power scavenger, dual capacitive cavities.

INTRODUCTION

Electrostatic micro power scavenger has drawn world's attention of being a promising solution to produce affordable, lightweight, easy to use micro-power sources for autonomous systems. One of popular designs of MEMS electrostatic power scavenger is using parallel plate structure forming capacitive cavity. Many groups have fabricated MEMS power scavenger using parallel plate structure in comparatively large scale (normally larger than 1 cm^2) forming single capacitive cavity [1, 2]. However, no group has developed such device with two capacitive cavities in mm^2 scale. Our 2×2 mm^2 MEMS electrostatic power scavenger is unique in the use of a dual-cavity design and electroplated nickel as main structural material. When the capacitance increases for one cavity, it decreases for the other. This allows using both up and down directions to generate energy [3, 4]. In this paper, the design, modeling, fabrication and testing of our MEMS electrostatic power scavenger with dual cavities will be presented. The device has been found with resonance band around 500 Hz. The device characterizations under various excitation conditions will be reported in details.

DESIGN AND FABRICATION

Our 2×2 mm^2 MEMS electrostatic power scavenger (Fig. 1) consists of a movable plate suspended between two fixed plates. Thin layers of Cr and Au were deposited and patterned to form the fixed plates, bottom and top electrodes, trace lines, and the seed layer at location corresponding to the anchors and bonding tabs. The movable plate with serpentine suspension beams and anchors are made of electroplated nickel. Five gold stoppers were electroplated on the fixed plates to prevent snap-down of the movable plate by overwhelming electrostatic force. SiO_2 and Si_3N_4 thin layers were patterned on the fixed plates to insulate the stoppers and enhance the dielectric property of the capacitive cavities.

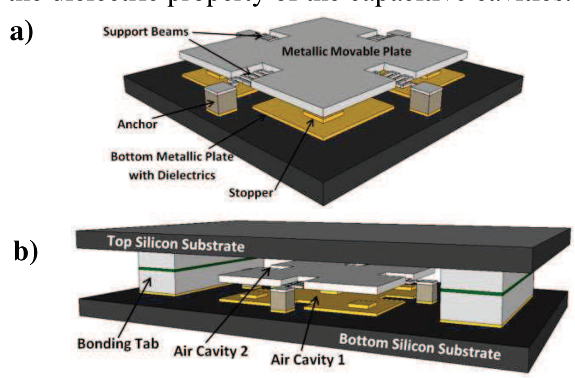

Fig. 1: 3D Schematic of MEMS electrostatic power scavenger, a) structure of movable plate, b) whole view of bonded device with dual cavities.

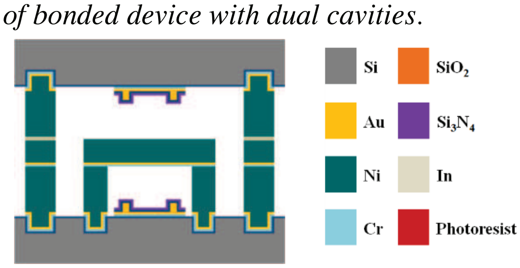

Fig. 2: Fabrication schematic of MEMS electrostatic power scavenger with dual cavities.

The device was suspended by removing the 30μm thick photoresist sacrificial layer using photoresist stripper in a sonic agitation bath. The second cavity was formed by fabricating a second substrate with fixed plate and electroplated nickel/indium bonding tabs, and then both substrates were aligned and bonded at 200 °C (Fig. 2).

MODELING

There have been extensive dynamic studies on basic designs of MEMS power scavenger with parallel plate structure, which incorporate the nonlinear electrostatic, elastic, and squeezed film damping in the models [5-7]. Most of researcher didn't consider rotational motion of the movable plate which was treated as having only translational degree of freedom [8]. However, in the real world, rocking instability of the movable (perturbations that may result in plates no longer in parallel to each other) is inevitable. In other words, the tips of the moving plate are very likely to hit the stoppers. A typical model in Fig. 3 illustrates the device with onset of rocking instability. When the device is being charged, the voltage varies as the movable plate was driven into motion by sinusoidal excitations. Low DC voltage battery on the left of Fig. 3 is used to charge the device, and the raised voltage as the plate vibrates is released to the battery on the right. Diodes are used to prevent the charge from flowing backwards.

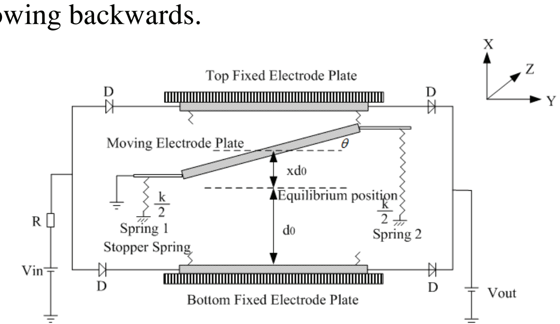

Fig. 3: Modeling schematic of eletrostatic power scavenger with dual-cavity involing rocking instability.

The movable plate is subjected to nonlinear electrostatic force F_e, linear suspension force and sinusoidal excitation force F_{ex}. The stoppers with high stiffness are necessary to prevent the snap down of movable plate by overwhelming electrostatic force. Equation (1) was developed to simulate the elastic nonlinear force of the stopper (stopper high equals 20% of capacitive gap) which may impact on the movable plate.

$$F_{st} = \begin{cases} k_2 d_0 \left|0.8 + L_r\right| / (1 + L_r) & -1 < L_r \le -0.8 \\ 0 & -0.8 < L_r < 0 \end{cases} \quad (1)$$

Where L_r is the dimensionless displacement of tip to the equilibrium level, d_0 is the initial gap between the plates and k_2 is spring constant of the stoppers. The sinusoidal excitation force applied on the movable plate is simulated by equation (2).

$$F_{ex} = \alpha m (2\pi\gamma f)^2 \cos(2\pi\gamma f t) \quad (2)$$

Where α is the imposed motion amplitude, m is the mass of the movable plate, γ is the ratio of the forcing frequency to the natural frequency and f is the natural frequency. When the device vibrates with rocking, the deflection angle θ of movable plate will affect the nonlinear capacitance as in equation (3), and the electrostatic force is given by equations (4) and (5). The equation (4) represents the electrostatic force when the device is in charging or discharging stage, the equation (5) presents the electrostatic force when it is not in charging or discharging stage.

$$C(x,\theta) = \int_0^A \frac{\varepsilon dA}{g(x)} = \frac{\varepsilon L}{\theta} \ln\left(\frac{d_0 + d_0 x + \theta W/2}{d_0 + d_0 x - \theta W/2}\right) \quad (3)$$

$$F_e = -\frac{\partial U}{\partial x} = -\frac{\partial}{\partial x}\left(\frac{Q^2}{2C^2}\mathrm{C}(\mathrm{x},\theta)\right) = \frac{V^2}{2}\frac{\partial}{\partial x}(C(x,\theta)) \quad (4)$$

$$F_e = -\frac{\partial U}{\partial x} = -\frac{\partial}{\partial x}\left(\frac{Q^2}{2C(x,\theta)}\right) = -\frac{Q^2}{2}\frac{\partial}{\partial x}\left(\frac{1}{C(x,\theta)}\right) \quad (5)$$

Where ε is the permittivity of air, $g(x)$ is the varying gap, θ is the deflection angle of the movable plate, L, W and A is the length, width and area of the movable plate, U is potential energy stored in capacitive cavity, and ∂x is differential displacement of the movable plate. Equation (6) was developed to model the translational motion of the movable plate based on Newton's second law. Equation (7) was developed to model the movable plate with rotational motion (rocking instability) based on the law of rotation.

$$m d_0 \ddot{x} = -c_1 d_0 \dot{x} - k d_0 x + F_{st} + F_e + F_{ex} \quad (6)$$

$$I_\theta \ddot{\theta} = -c_2 \dot{\theta} - \frac{k}{8} L^2 \theta + M_e \quad (7)$$

Where x is the dimensionless displacement, c_1 is the damping coefficient, k is the spring constant, c_2 is the damping coefficient for the rotational degree of freedom, I_θ is the inertial constant of the movable plate and M_e is rotational moment of electrostatic force. We use equation (6) and (7) together to analyze the dynamic responses of the device with and without rocking instability. Numerical solutions of the equations of motion have led to the findings of very unusual responses. Fig. 4 shows asymmetric responses when one end of the plate impact the fixed plates twice while the other end only once. Fig. 5 shows plate responses dominated by multiple impacts of the two ends with the fixed plate. When the motion is dominated by the impacts, the plate capacitance change is much less than when the plates are parallel. The harvested power is thus much reduced. Table 1 and Table 2 show the comparison of the harvested power for model that does not include rotational degree of freedom and for model that does include the rotational degree of freedom. We can see that the power generation is dramatically lowered by the onset of rocking instability. However, the harvested power is overestimated otherwise.

a)

b)

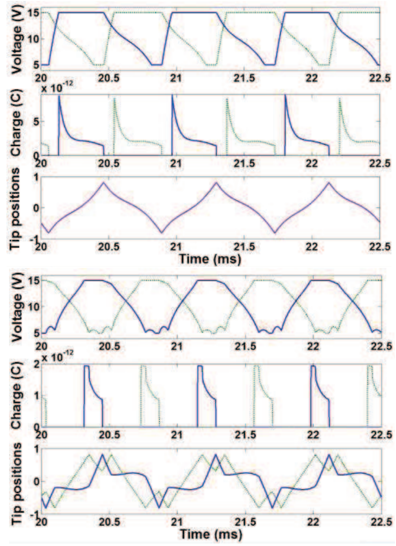

Fig. 4: Dynamic responses of a dual-cavity model under 20 µm, 1200 Hz excitation, a) without rotation, b) with rotation.

a)

b)

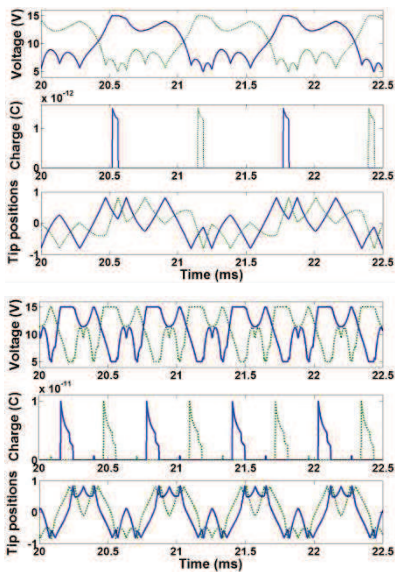

Fig. 5: Dynamic responses of a dual-cavity model with rotation, a) under 80 µm and 800 Hz excitation, b) under 80 µm and 1600 Hz excitation.

Table 1. Numerical solution results of average power (average current × output voltage) produced by a dual cavity model without rotation.

Imposed Motion Amp (µm)	Average Power (µW) Produced By a Double Cavity Model Without Rotation					
	Forcing Frequency= γ* Natural Frequency					
	γ=0.5	γ=1.0	γ=1.5	γ=2.0	γ=2.5	γ=3.0
80	10.54	27.85	49.74	68.68	93.66	121.9
60	10.35	23.92	37.94	58.86	74.71	94.74
40	0	21.75	42.64	58.52	64.7	93.39
20	0	21.02	32.98	46.03	59.97	76.15

Table 2. Numerical solution results of average power (average current × output voltage) produced by a dual cavity model with rotation.

Imposed Motion Amp (µm)	Average Power (µW) Produced By a Double Cavity Model With Rotation					
	Forcing Frequency= γ* Natural Frequency					
	γ=0.5	γ=1.0	γ=1.5	γ=2.0	γ=2.5	γ=3.0
80	4.29	1.34	9.81	23.52	27.84	30.24
60	5.42	9.84	13.62	21.36	29.24	39.63
40	0	9.82	10	18.70	24.7	43.14
20	0	17.25	6.31	0.17	12.14	31.09

DEVICE CHARACTERIZATION

MEMS electrostatic power scavenger with dual cavities has been successfully fabricated using surface micromachining technology (Fig. 6). The device was experimentally characterized using a PCB test board mounted on a shaker and National Instruments' Labview with a NI USB-6218 DAQ (Fig. 7). A typical time domain plot of output voltage across the load resistors under 15V DC bias, 500 Hz and 2.090 g sinusoidal excitation is shown in Fig. 8. The RMS voltage across two 5 MΩ load resistors was measured as function of frequency under various strength of sinusoidal excitation.

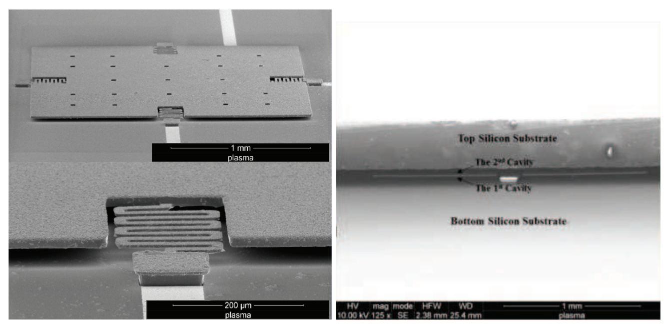

Fig. 6: SEMs of MEMS electrostatic power scavenger before and after bonding the second cavity.

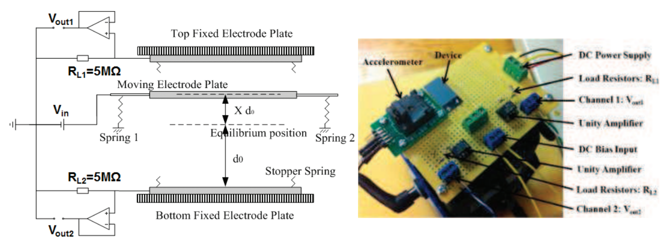

Fig. 7: The electrical testing circuit and real experimental setup for device characterizations.

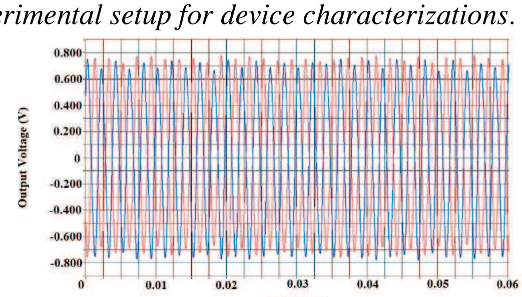

Fig. 8: A time domain plot of output voltage across the load resistors.

The device's resonance was observed around 500 Hz under different DC bias of 9 V and 15 V (Fig. 9a). Corresponding total power measured across load resistors are shown in Fig. 9b. The device was also characterized under a fixed frequency of 500 Hz while sweeping the excitation strength, the total measured power from two load resistors increases as excitation was strengthen and finally saturates in extreme high excitation level. A maximum power of 225 nW was achieved under a high DC bias of 15 V and intense excitation above 5g (Fig. 10).

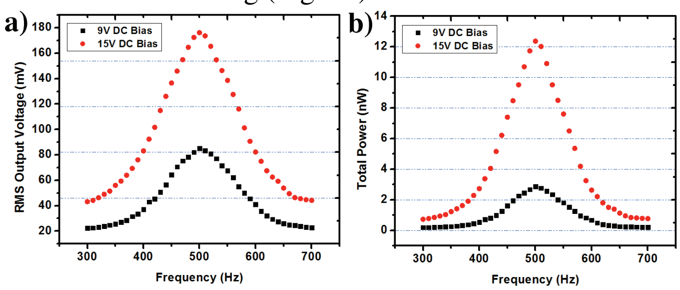

Fig. 9: a) Frequency sweeps with bias DC of 9 V and 15 V under RMS excitation of 1.026 g, b) Measured total power from two capacitive cavities as frequency sweeps.

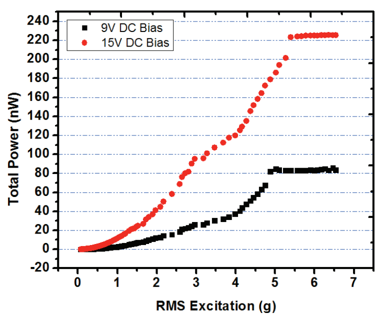

Fig. 10: Excitation sweeps with bias DC of 9 V and 15 V under 500 Hz.

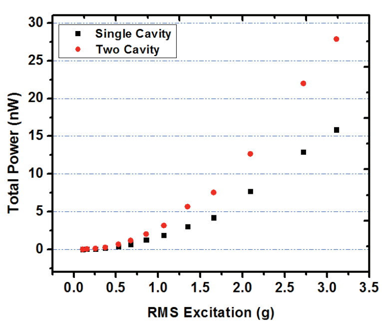

Fig. 11: Comparison between single and two cavity devices under 500 Hz and various strength of excitation.

The output power from a single cavity device and a two cavities device under identical vibration conditions were measured and compared, which indicates a 1.7 times higher power can be produced from the two cavities device (Fig. 11).

CONCLUSION

Prototype of MEMS electrostatic power scavenger with dual cavities was successfully fabricated using surface micromachining technology. We have summarized findings based on the numerical simulations of equation of dynamic motion of the movable plate with rotational degrees of freedom on power harvesting of capacitive cavities. The device was characterized under various excitation conditions. The device's resonance about 500Hz was observed. A maximum measured power of 225 nW across load resistors was achieved under extreme excitation and high bias DC. The results also indicates that the device with two capacitive cavities effectively enhance the harvested power comparing to single cavity device.

REFERENCES

[1] B. C. Yen and H. L. Jeffery, "A Variable Capacitance Vibration-to-electric Energy Harvester," *IEEE Trans. Circuits Syst.*, vol. 53, no. 2, pp. 288–295, 2006.

[2] Y. C. Lee, Y. Chiu, "Low Cost Out of Plane Vibrational Electret Energy Harvester", *Proc. PowerMEMS*, Seoul, Korean Nov. 2011.

[3] J. Lin, J. X. Zhu, M. Sonje, N. Yuksek, Z. C. Feng, and M. Almasri, "Multi-cavities MEMS Capacitive Plates for Power Harvesting", *Proc. PowerMEMS*, Seoul, Korean, Nov. 2011.

[4] J. Lin, J. X. Zhu, M. Sonje, Y. S. Chang, Z. C. Feng, and M. Almasri, "Two-cavity MEMS Variable Capacitor for Power Harvesting", *J. Micromech. Microeng.*, vol. 22, no. 6, 2012.

[5] J. F. Rhoads, S. W. Shaw and K. L. Turner, "Nonlinear dynamics and its applications in micro- and nanoresonators", *J. Dynamic Systems, Measurement and Control,* 132, 034001-1-14, 2010.

[6] E. K. Chan, K. Garikipati and R. W. Dutton, "Characterization of contact electro-mechanics through capacitance-voltage measurements and simulations", *IEEE Journal of MEMS*, vol. 8. No. 2, pp. 208-217, June 1999.

[7] P. B. Chu and K. S. J. Pister, "Analysis of closed-loop control of parallel plate electrostatic microgrippers", *Proc. IEEE International Conference Robotics and Automation*, pp. 820–825, 1994.

[8] I. S. Joseph and E. B. Bernhard, "Dynamics and control of parallel-plate actuators beyond the electrostatic instability", *The 10th International Conference on Solid-State Sensors and Actuators*, Sendai, Japan , vol. pp. 474-477, June 7-9, 1999.