CAPACITIVELY-TRANSDUCED MECHANICALLY-COUPLED BANDPASS FILTER IN ELECTROPLATED NICKEL FOR HARVESTING ENERGY FROM AMBIENT VIBRATIONS

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Abstract: MEMS energy harvesters for powering miniaturized sensors have provided new opportunities in applications. This paper describes the design and fabrication of a new class of vibration energy scavengers based on mechanically coupled resonating proof masses for harvesting low-frequency ambient vibrations with high efficiency by widening of the passband. Electroplated nickel was chosen as the structural material for ease of fabrication and its compatibility with post-CMOS integration processes. Capacitive transducers were adopted for efficient conversion of mechanical oscillation between the parallel plates into electricity and simple integration with ICs.

Keywords: Capacitive energy storage, Bandpass filter, MEMS energy harvester, SU-8, Molding, Electroplating

INTRODUCTION

The implementation of MEMS energy harvesters to power miniaturized sensors for a variety of applications, such as structural health monitoring, process control, and healthcare has attracted tremendous attention from both academia and industries [1]-[4]. At present the key challenge hindering the deployment of MEMS energy scavenger with acceptable efficiency is the lack of techniques that automatically adapt its resonance characteristics to that of the ambient vibration. Several different technologies have been developed such as capacitive, piezoelectric or magnetic-inductive [5], [6] in order to convert the power source from the environment (solar energy, vibration and motion, temperature gradient, fluidic flow, air flow, pressure variation, etc.) into electrical energy. Several design challenges are related to the development of this kind of devices, such as the dynamic dimensioning, the power efficiency and the structural reliability. Some strategies were investigated in order to provide these characteristics [7].

It is possible to design an energy scavenger whose resonance frequency can match the frequency of a vibration source. However, the key challenge hindering the deployment of MEMS energy scavenger with acceptable efficiency is the lack of techniques that automatically adapt its resonance characteristics to that of the ambient vibration. A sufficiently wide passband is then required in order to meet entire range of frequencies provided by the vibrating environment.

This paper reports the activity of design and fabrication of energy harvesters for applications in the range of 300-700Hz. Capacitive strategy was adopted to efficiently transform the mechanical oscillation into electricity signal.

By using the strategically-designed constituent coupling springs and proof masses, the composite microsystem with bandpass filtering characteristics have great potential to obtain greatly improved efficiency. Structural and modal FEM simulations were used for the dynamic optimization of the design. The electroplated nickel was applied as structural material for ease of fabrication and its compatibility with post-CMOS.

DESIGN AND SIMULATION

The capacitive energy harvesting relies on the relative displacement between two charged parallel plates which are connected to a suspended proof mass by elastic springs. In order to obtain the high capacitance and maximize power output, substantial displacement is then required and achieved by the kinematics of the mass and the in-plane solution with comb drive structures of inter-digital electrodes which can be designed in the same level on-chip. Both variable area of electrodes (overlap strategy) and variable gap between the electrodes (gap closing strategy) are proposed as two different designs. The former one provides a linear relation between the mass displacement and the output voltage while the latter one is nonlinear. Both designs introduce a giant proof mass combined with two series of comb electrodes varying in geometrical dimensions which are connected with output pads via springs. The natural frequency of harvesting device is due to the effective mass and stiffness of the springs while the electrical power output is dependent on the geometrical characteristics of comb drives.

A wide bandpass accommodating the entire range of frequencies for the targeted sources of vibrations is preferred for energy harvesters to allow maximum energy conversion from mechanical oscillation in environment. Although the ambient vibrations are random and unpredictable, the typical resonance characteristics of the hosting systems such as building, bridge, etc., often reside within a specific range of frequencies. Several solutions have been reported to amplify the oscillation bandwidth of devices. It is possible to build a set of scavengers with different geometry tuned within a precise value of resonance frequency [7], or apply electrical preloads to vary the global stiffness [3], or tune the resonance by a stiffening/softening procedure of the structure using axial loads [8].

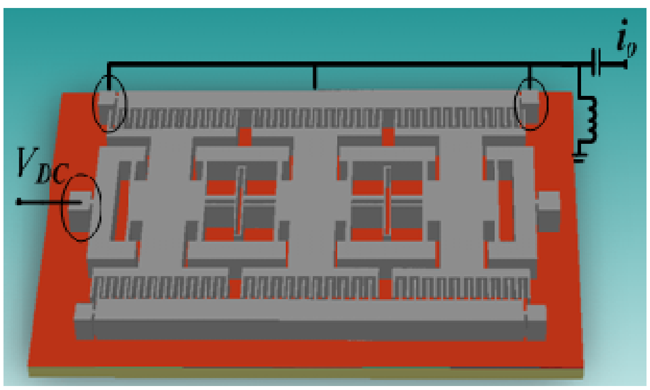


Fig. 1: 3-dof harvester with amplified bandwidth.

Table 1: FEM simulated modal responses of sample 3-DOF harvesters.

Type	Intermediate spring type	Res. mode I [Hz]	Res. mode II [Hz]	Res. mode III [Hz]
A	1	419	551	750
	2	419	485	598
	3	419	463	543
B	1	356	508	723
	2	356	433	560
	3	356	408	499
C	1	308	479	709
	2	308	397	536
	3	308	368	469

As shown in Figure 1, the approach adopted here is to mechanically couple several identical energy harvesting proof masses to form a bandpass mechanical filter while overlapping its passband with the environment by designing the coupling springs. The resultant filtering frequency spectrum is characterized by multiple resonance peaks corresponding to several resonance modes. The bandwidth is mainly dependent on the stiffness of the coupling spring whose characteristic can also be modified by adopting the stiffening/softening strategy and applying static axial loads. Three different spring types are designed and built, as reported in Figure 2. Figure 3 and Figure 4 present a typical bandpass frequency characteristic of a complete 3-DOF spring-proof mass system with simulated mode resonance frequencies reported in Table 1. The simplification of the design (same shape and dimensions can be applied in all the harvesters) and the variation of bandwidth amplitudes by different springs are the main advantages of this design.

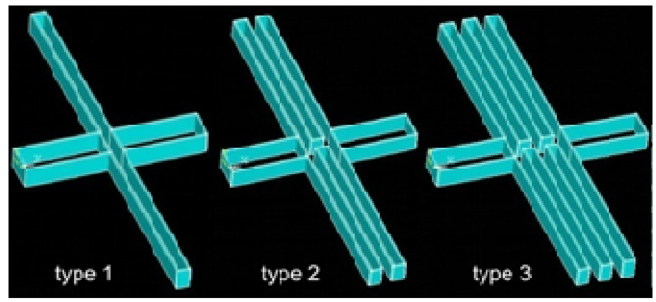


Fig. 2: Types of intermediate springs.

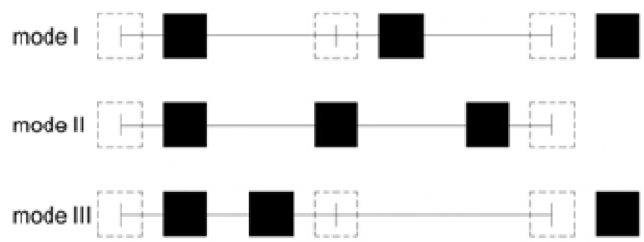


Fig. 3: Modal displacements of 3-dof harvesters.

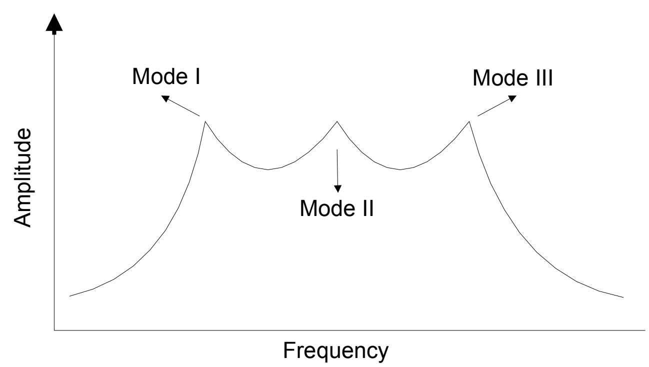


Fig. 4: The frequency response function of the coupled harvesters.

Structural FEM models are built in order to simulate the static and dynamic behavior of harvesters by using the commercial tool Ansys 11.0. Material properties assumed for nickel are: Young's module E = 195GPa, Poisson's ratio $\nu = 0.3$ and density $\rho = 8.9 \cdot 10^{-15} kg/\mu m^3$. A mesh based on 10 nodes tetrahedral structural elements is applied. Static and modal analyses are performed in order to calculate the static stiffness of the device and the resonance frequencies. A huge proof mass and low stiffness are required since the application in bandpass filter deals with relative low resonance frequency targets. The device is 100μm thick in all different dimensions and the static stiffness is calculated by a FEM model as the ratio between a static force and the resulting displacement of the suspended mass. Stiffness values of the springs from FEM simulation are k_1 = 23.2μN/μm, k_2 = 11.0μN/μm and k_3 = 7.2μN/μm for type 1, 2 and 3 in Figure 2 respectively.

FABRICATION

As shown in Fig. 5, the fabrication process starts with a silicon wafer and followed by a 2um silicon dioxide as electrical isolation layer between the silicon substrate and the eventual nickel harvester. Then, a 3μm amorphous silicon layer is deposited by PECVD to serve as a sacrificial layer. Next, patterned by the first mask, via holes are dry etched through amorphous silicon to define the anchors. Seeding layers (20nm Cr and 25nm Cu) are evaporated for electroplating process. Then, the electroplating mold with high aspect ratio in SU-8 100 negative photoresist is patterned via UV lithography by using the second mask.

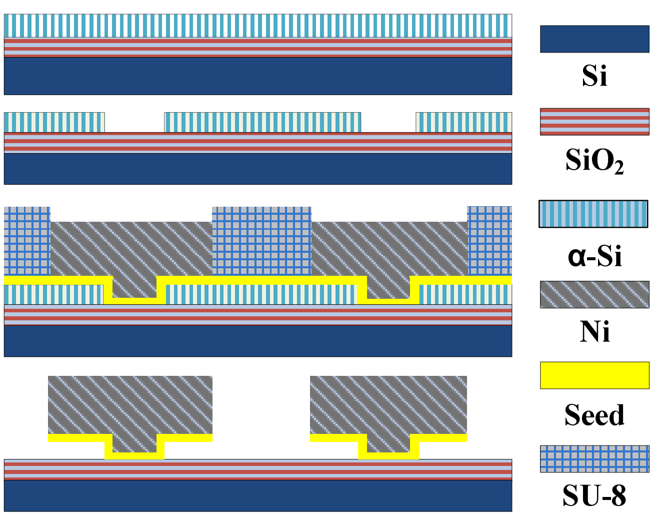
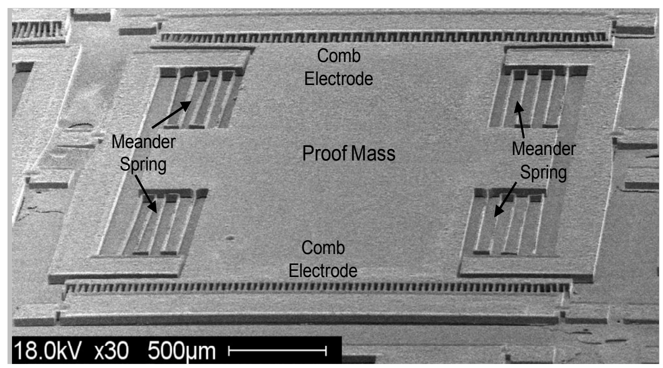
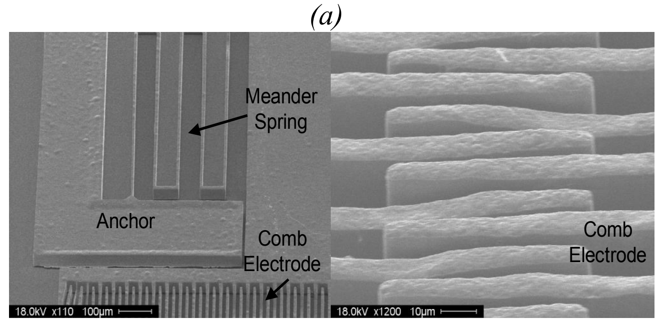


Fig. 5: The fabrication process of energy harvesters.

A 100μm thick nickel microstructure is then electroplated to form the body of the MEMS energy scavenger. The electroplating process can be proceeded in the electrolyte under the temperature of 50ºC which is low enough to post-process over the finished Integrated Circuits. The electroplating solution with a pH value of 4 consists of nickel sulfamate (350g/l), boric acid (40g/l), nickel chloride (10g/l) and sodium lauryl sulfate (1g/l). The current density applied here is about 10 mA/cm^2 and the electroplating speed is about 12 μm/h. After electroplating, NANO™ Remover PG is adopted to remove the SU-8 mold between 60ºC to 80ºC, then followed by a plasma etching process in order to remove the SU-8 residues [9]. Then, the seed layers are etched away by chromium and cupper etchants respectively. Finally, a unique dry etching process [10] is adopted to efficiently remove amorphous silicon sacrificial layer while minimizing potential stiction issues, especially for a relatively large-dimensional proof mass required in the design. The SEM pictures of device are shown in Figure 6. Compared to the wet realeasing process which introduces some inherent problems like stiction and low etch rate, dry releasing process provides good efficiency on etch rate, Si to SiO_2 selectivity and can be compatible with post-CMOS integration processes.



(a)



(b)

Fig. 6: (a) and (b) SEM pictures of fabricated energy harvesters.

CONCLUSION

Vibration energy scavengers in application of bandpass filter within a low frequency range are designed and fabricated. Structural and modal FEM simulations are conducted for optimizing the dynamic response of the design. The nickel electroplating process is employed for low-cost fabrication and simple modular integration with ICs.

FUTURE WORK

The measurement of electrical output of fabricated scavengers is ongoing by using a mechanical vibration generator that sweeps across the frequency range of interest to mimic the potential ambient vibrations from environment [11], [12]. The device can be tested using the shaker and measurement instruments shown in Figure 7.

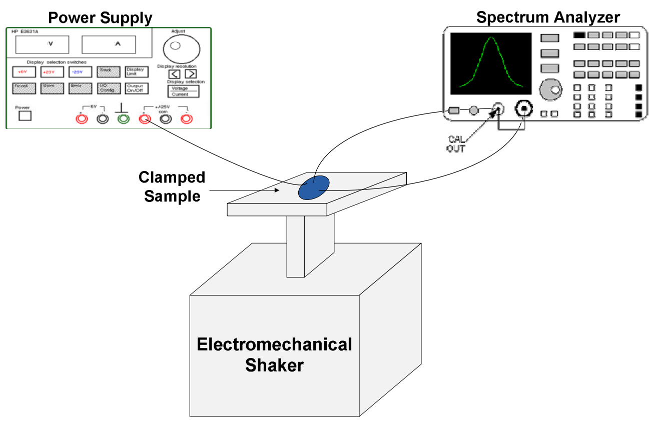


Fig. 7: Measurement setup.

ACKNOWLEDGMENTS

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