SURFACE MICRO-MACHINED FABRICATION OF CAPACITIVE TRANSDUCERS FOR ELECTROSTATIC ENERGY HARVESTERS

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Abstract: This paper reports the design, fabrication, and testing of a capacitive transducer for electrostatic energy harvesting using surface micro-machined MEMS fabrication process. Surface micro-machined processes have been used to fabricate compliant suspension beams (low spring constant value) for large inertial mass as well as large capacitance variability. Simulation results show an improvement over previous similar designs. The capacitive transducer prototype has a size of (2.5mm x 1.5mm). The experimental results show the generation of 65mV at a resonance frequency of 1100Hz for 2g_{rms} acceleration using a 50MΩ load resistance. The configuration allows array-like operation which can have a power density of 3.9mW/cm^3.

Keywords: Electrostatic, Capacitive, Surface micromachining, Flip-chip

INTRODUCTION

Harvesting vibration energy has gained considerable attention in the last decade. The abundance of vibration in different environments including human, domestic and industrial environments was one of the motivations behind investigating its use as a source of electrical energy. In addition to that, the advances in integrated circuits which allow the use of ultra-low power circuits as well as using novel power management systems for burst operation of sensors opened the door for battery-less systems aiming for low cost, sustainable and embedded operation.

Current vibration energy harvesters are based on piezoelectric, electromagnetic, or electrostatic [1]. Each of the three techniques aims to damp a spring-mass system with base excitation to transducer the vibration energy into electrical energy. Fig.1 shows the mechanical model of a vibration energy harvester showing the spring-mass system with B_e represents the electrical damping and B_m is the mechanical damping.

For efficient conversion, resonant operation of the spring-mass system is required as well as the proper alignment of the resonance frequency with the fundamental frequency of the vibration source. The free-running natural frequency of the spring-mass system is equal to:

$$\omega_n = \sqrt{\frac{k}{m}} \quad (1)$$

Most of the vibration sources' fundamental frequencies are below 200Hz. Fabricating miniaturized transducers with resonance frequencies equal to such vibration frequencies is challenging.

In this paper, the challenges facing producing low resonance frequency miniaturized transducers are discussed. A novel suspension system based on

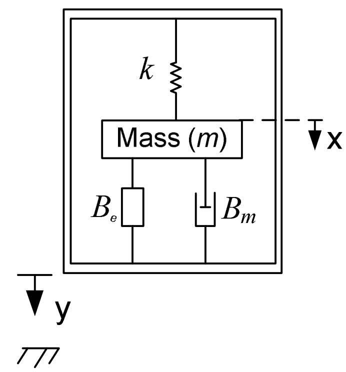

Fig. 1: Vibration energy harvesting mechanical model

surface micromachining processes is proposed The system can contribute in lowering the resonance frequency of miniaturized capacitive transducers of electrostatic energy harvesters.

The paper is organized in five sections. Section one is introduction about vibration energy harvesting. Section two describes the challenges facing miniaturized capacitive transducers as well as the new surface micro-machined suspension system. Section three illustrates the fabrication and assembly of the capacitive transducer prototype. Section four presents the testing setup and results for the prototype. Finally, Section five illustrates the conclusions and discussions.

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CAPACITIVE TRANSDUCER DESIGN AND FEATURES

Capacitive transducers in electrostatic energy harvesters (ESEH) have two important parameters that affect the amount of harvested energy. The first parameter is the mass of the suspended block (m). It affects the inertia of the system. The larger the mass m, the larger the stroke will be at resonance and therefore, the larger the available vibration energy to harvest.

The second parameter is the variability of the capacitive transducer, also termed as tuning range, affects the transduction capacity of the electrical system [2]. As a result, out-of-plane variable capacitors are more frequently used as a capacitive transducer in ESEHs for their wide tuning range. Such configuration requires suspension beams with low stiffness in the in-plane direction and high stiffness in the out-of-plane direction. Therefore, beams with high aspect ratio are required. Figure 2 shows a conventional suspension system for in-plane motion. The ratio between the beam stiffness in the x-direction and the z-direction depends on the type of the beams. The highest ratio is for single beams and is given by:

$$\frac{k_x}{k_z} = \left(\frac{b}{h}\right)^2 = \frac{1}{r^2} \qquad (2)$$

where *b, h,* and *r* are the beam width, thickness, and aspect ratio , respectively.

Miniaturizing of the ESEH capacitive transducers requires minimization of the gap between the capacitor electrodes to ensure the existence of sufficiently large electrical capacitance to initiate the conversion cycle with enough electrical energy stored in the capacitor [2].

In comb finger in-plane topologies making the gap between the fingers small with increasing the finger length as well as increasing the number of fingers makes the suspended structure very sensitive to any mismatch between the suspension beams leading to short circuit between the capacitor's fingers [3].

In parallel plate in-plane topology, decreasing the gap makes the suspended structure liable to pull-in by the electrostatic forces.

The deflection due to the electrostatic force depends on the value of the applied voltage. The maximum voltage that can be applied without collapse is the pull-in voltage of the capacitor. Using the formula of the static pull-in voltage [4], the maximum voltage is:

$$V_{\max} = V_{pull-in} = \sqrt{\frac{8}{27}\frac{k_z d^3}{\varepsilon_0 A_c}} \qquad (3)$$

where A_c and d are the capacitor's electrodes area and the gap between them. Substituting for k_z using (2) and (1) while assuming silicon as a substrate, the resulting maximum voltage is:

$$V_{\max} = \omega_{nx}\sqrt{\frac{8}{27}\frac{h\rho_{Si} r^2 d^3}{\varepsilon_0}} \qquad (4)$$

where ρ_{Si} is the silicon density. Fig. 3 shows a plot of the maximum voltage as a function of the natural frequency in the x-direction for different combinations of h and r with $d=3\mu m$. It is clear that for small gaps, low resonance frequency operation will decrease significantly the maximum voltage that can be applied on the capacitor and therefore, will decrease significantly the amount of electrical power produced.

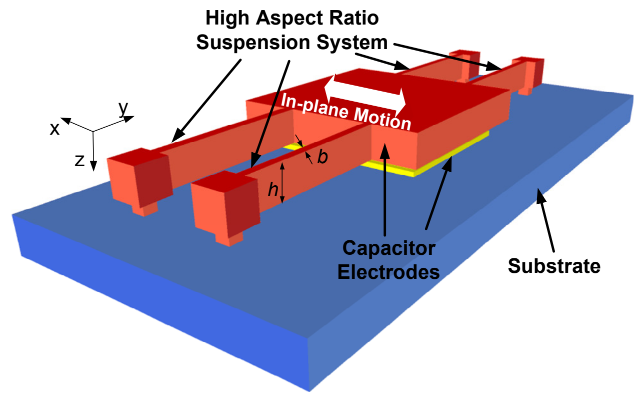


Fig. 2: Conventional suspension beams

To decouple the maximum voltage applied and the system lateral resonance frequency as well as the need of a high aspect ratio beams, a new suspension system is proposed in this paper. The idea of the new suspension system is to use dimples for suspension instead of the high-aspect beams similar to electrostatic motors and the use of compliant beams instead to act as ropes rather than suspension to guide the motion laterally in an in-plane fashion.

Fig.4 illustrates a typical suspension part of the transducer. The beams are made using surface micro-machining process to ensure the compliance of the beams. The beams are connected to suspension carts with dimples beneath them to decrease the friction and prevent stiction. The two electrodes are made rigid by using flip-chip assembly of two substrates with each holding one electrode. The gap is defined by using a gap adjusting post that prevents pull-in and ensure uniform gap. In the next section, the fabrication of a capacitive transducer prototype using

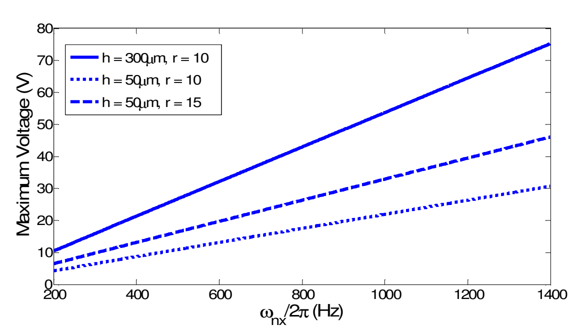


Fig. 3: Maximum applied voltage for different resonance frequency.

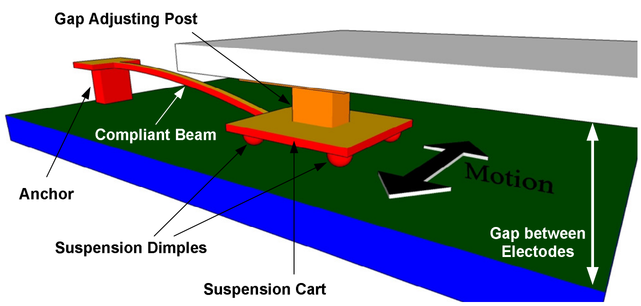


Fig. 4: Suspension system for surface micro-machined transducer

the proposed suspension is illustrated.

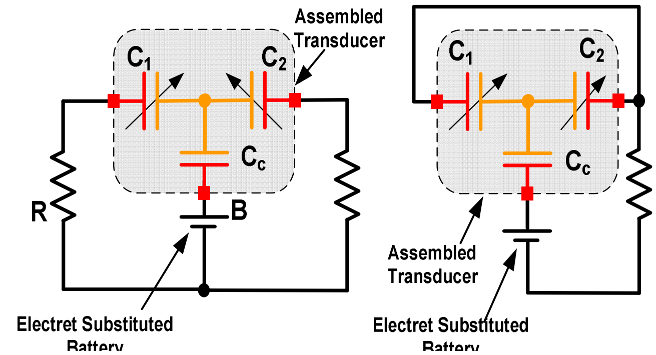
TRANSDUCER FABRICATION AND ASSEMBLY

The capacitive transducer circuit used to demonstrate the new suspension technique is based on the topology proposed by Sterken et al [5]. However, the implementation is based on interdigitated in-plane parallel plate capacitors [6]. The transducer consists of two variable capacitors that can have two modes of operation depending on the variability fashion of the variable capacitors as shown in Fig. 5. The topology can use electret layer (permanently-polarized dielectric) as a source of charge. Such layer allows self operation with the need of external source.

The size of the transducer is equal to (2.5mm x 1.5mm). The transducer is made of bonding two chips together using flip-chip technique. Fig. 6 shows an extended 3D schematic of the transducer. Such configuration has three advantages. First, it ensures the rigidity of the movable plate for a uniform capacitive gap. Second, it provides extra mass for energy harvesting. Third, it allows arraying of the transducer by having multiple bottom chips and one common upper suspended chip. The guiding beams are made of folded beams to allow long in-plane travel.

The fabrication of the bottom chip in Fig. 6 is done using PolyMUMPs process [7]. This commercial process offered by MEMSCAP has three structural layers and two sacrificial layers on silicon substrate coated with silicon nitride for isolation. This chip contains one of the capacitive electrodes and the suspension system. The suspension system has a cart-like structure with four pads connected to the guiding beams. These pads have the suspension dimples to prevent stiction. Moreover, the nitride layer present for isolation is used as an electret by electrically charging it after fabrication and assembly.

The upper chip was fabricated using a two mask process as shown in Fig. 7. This chip contains the



(a) *(b)*

Fig. 5: Possible connections of the transducer: (a) Double load (C_1 and C_2 are out of phase), (b) Single load (C_1 and C_2 are in- phase).

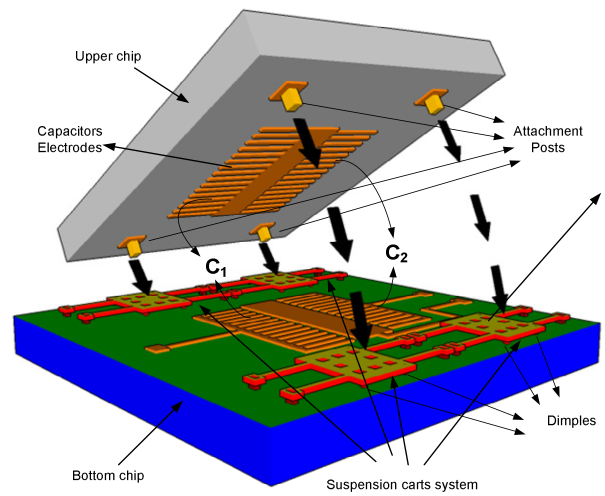


Fig. 6: An Extended 3D Schematic of the capacitive transducer prototype

upper electrodes and replica pads for bonding. This chip allows the control of the capacitors gap using a post-like structure fabricated using gold electroplating.

The assembly of the transducer is performed by attaching the PolyMUMPS chip to an Alumina assembly substrate using Epoxy for handling. Further more, the two chips are aligned together and bonded together through flip-chip technique. Fig. 8 shows a close SEM of the transducer with the two chips bonded showing the beams released.

TESTING SETUP AND RESULTS

The testing setup is build using a piezoactuator attached to an L-shaped base and an accelerometer which is attached to this base to measure the acceleration of the piezoactuator. The piezoactuator allows frequency sweep for a wide range of frequencies. Fig. 9 shows the testing setup used to

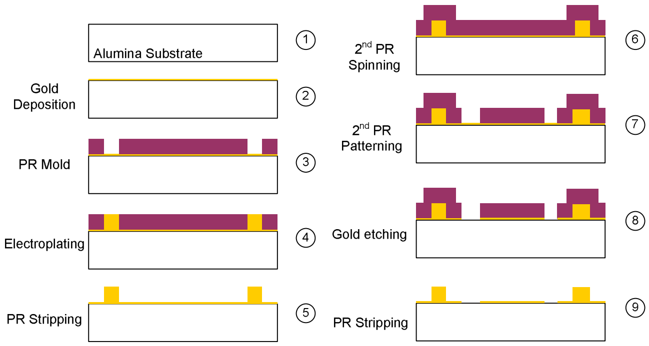


Fig. 5: Fabrication process flow for the bonded chip

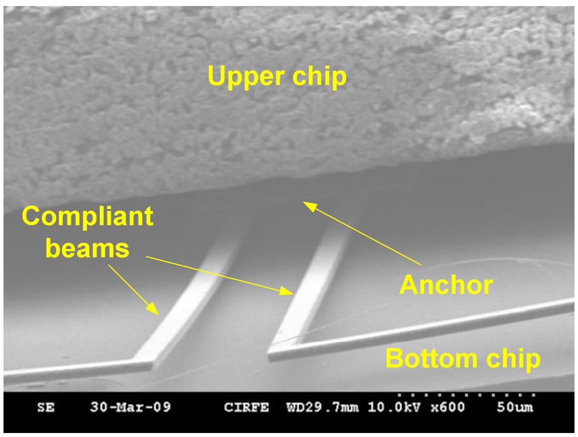


Fig. 8: A close SEM picture of the transducer after release showing the guiding beams

test the resulting transducer. Fig. 10 shows an initial experimental result of the frequency sweep obtained for 2g rms acceleration using a 50MΩ load resistance. The nitride layer was charged by a 300V to act as a source of charge for the capacitors. Although only 65mV peak voltage was obtained at a resonance frequency of 1100 Hz, the configuration allows array-like operation which can have a power density of $3.9 mW/cm^3$.

CONCLUSIONS AND DISCUSSIONS

This paper presented a novel suspension system for in-plane capacitive transducers based on surface micro-machined MEMS process. The new system allows the use compliant suspension beams for suspending large inertial mass. The capacitive transducer prototype with the new suspension system has a size of (2.5mm x 1.5mm). The experimental results show the generation of 65mV at a resonance frequency of 1100Hz for $2g_{rms}$ acceleration using a 50MΩ load resistance. Although the frequency is still high, further reduction in the resonance frequency can be obtained by adding additional mass without affect the gap of the capacitor transducer.

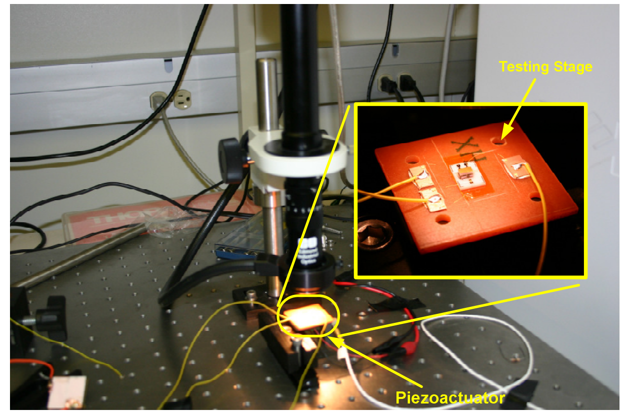


Fig. 6: Testing setup for the assembled transducer

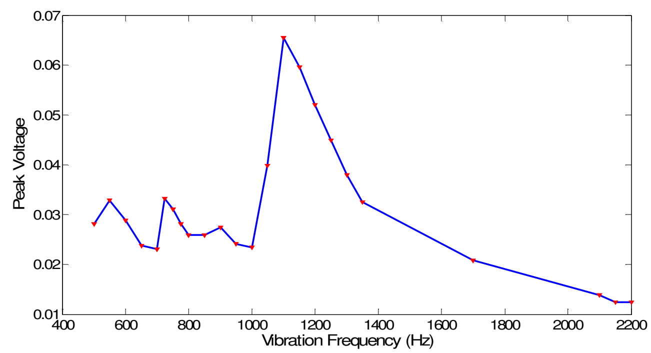


Fig. 10: Experimental test results for a load resistance of 50MΩ using a vibration of acceleration equal to 2grms.

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