A SELF-POWERED MICRO TRIBOELECTRIC ACCELEROMETER WITH HIGH SENSITIVITY

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ABSTRACT

This work presents an improved design and fabrication of a triboelectric micro accelerometer with significant output voltage and sensitivity: maximum of 1.8 V when tested at 2-10 g with maximum sensitivity of 186.5 mV/g at resonance. We applied genetic algorithm-based optimization to maximize the sensitivity by optimizing designs of serpentine springs. Our fabrication is simplified and features integrating triboelectric pair (Aluminum-Polyimide) as a proof mass and eliminates additional layers used before to provide inertia.

KEYWORDS

MEMS, accelerometer, polyimide, triboelectricity, sensitivity, self-powered, genetic algorithm

INTRODUCTION

The accelerometer is a electromechanical device that is used for vibrations measurements. They are one of the most important applications of MEMS because they are heavily used in the automotive industry. Capacitive accelerometers are very common accelerometers in which two parallel electrodes are charged with a power supply, the capacitive accelerometer works by correlating the relative motion of electrodes to the change in the capacitance. This is useful to make devices with different structural operation such as comb drives for in-plane motion [1, 2] and torsional drives with capacitance changes in rotational motion [3]. For out-of-plane motion, the effective capacitive accelerometer is made with parallel plates configuration where a movable electrode can move perpendicular to the substrate [4]. The capacitance variation for capacitive sensing is in the pF corresponding to excitations up to 100 g.

The main drawback of capacitive sensing is that it requires external power supply to sense the capacitance change in a charge amplifier circuit. To make a self-powered accelerometer, it is required to include transducer elements that convert motion to electricity. The piezoelectric materials have the special property of converting strain into electricity and vice versa. The piezoelectric accelerometers design mostly includes a movable structural beam with the piezoelectric strip on it, the main differences between piezoelectric accelerometers are the material and the design of the movable beam. Some of the known materials which have piezoelectric property are aluminum nitride (AlN), scandium aluminum nitride (ScAlN), and lead zirconate titanate (PZT) [5-7].

The disadvantage of piezoelectric accelerometers is the complex fabrication since polarization is required after annealing to get high sensitivity, also, the electrical output is greatly affected by the coupling of force. Triboelectric accelerometer is considered as a good alternative because of their easy fabrication and inclusion in MEMS fabrication. Triboelectric generators consist of two conductive and a dielectric layer. By design, external excitation causes rubbing of the dielectric on one of the conductive layers while the other conductive layer is used at the back of dielectric layer. The rubbing will cause negative and positive charges on the contacting layers because of the different affinity of gaining or losing electrons for both materials. Then, separation of the dielectric and the conductive layer causes voltage difference as the positively and negatively charged electrodes separate. The triboelectric generators are common in Macro scale with wide variety of triboelectric pairs such as polydimethylsiloxane (PDMS) with copper [8]. New research on minimizing the triboelectric generators to micro scale was started by Hamid et al. by using triboelectric pair of Teflon and aluminum. However, their fabrication process is outdated since they used UV-LIGA process, and it is hard to duplicate since they used polyimide as a sacrificial layer and the removal of it is done by 800 hours ashing process [9]. In our previous work, we managed to fabricate micro-triboelectric accelerometer with simpler process with the triboelectric pair of polyimide-aluminum [10]. Our process used sputtered aluminum as bottom layer, polyimide as the dielectric, silicon oxide as sacrificial layer, another sputtered aluminum as top layer, and a proof-mass layer of amorphous silicon, respectively. The output voltage generated from that work was 0.7 V at 10 g excitation at resonance frequency with sensitivity of 68.3 mV/g.

In this work, we optimized the design of the triboelectric accelerometer by using genetic algorithm to change the serpentine springs in top layer for maximizing output voltage and sensitivity. We altered the previous fabrication process for the triboelectric accelerometer by switching the placement of the polyimide layer to be attached to the top electrode hence eliminating the need to include a proof-mass layer.

GENETIC ALGORITHM-BASED OPTIMIZATION

Genetic algorithms have widely been used for design and optimization of MEMS structures in sensing [11] and energy harvesting [12] scenarios. In this problem, after we determine the size of center proof mass, genetic algorithm optimization is applied in the structural design of the serpentine springs that take space of area on the limited periphery of the proof mass and connect it to anchors. The spring is also made of aluminum and polyimide layers with its dimensional variables in consideration including number of folds, length, and width for each beam. Constraints of these variables come from micro-fabrication standard and the allocated chip area.

Given a set of these dimensional variables, the stiffness coefficients k_{eq} in out-of-plane direction can be found according to Castigliano's second theorem, as in Equation (1) where [S] is the compliance matrix. From the mechanical-electrical coupled equations for triboelectric accelerometers [10], the generated voltage at our desired operating frequency, 900Hz is obtained as in Equations (2)-(4):

$$k_{eq} = \#\ of\ springs \times \frac{S_{11}S_{22}}{S_{11}S_{22}S_{33} - S_{11}S_{23}^2 - S_{22}S_{13}^2} = m_{eq}\omega^2 \quad (1)$$

$$R\dot{q}(t) = V(t) = -\frac{q(t)}{A\epsilon_0}\left(g - z(t) - \frac{T_{PI}}{\epsilon_r}\right) + \frac{\sigma}{\epsilon_0}(g - z(t)) \quad (2)$$

$$m_{eq}\ddot{z}(t) = -c\dot{z}(t) - k_{eq}z(t) - m_{eq}a(t) - k_i(z(t) - g) \quad (3)$$

$$m_{eq}\ddot{z}(t) = -c\dot{z}(t) - k_{eq}z(t) - m_{eq}a(t) - \frac{q^2(t)}{2\epsilon_0 A} \quad (4)$$

where (3) and (4) represent scenarios before and after penetration, respectively.

We also evaluated the accelerometer sensitivity when sweeping the acceleration force from 2g to 10g. The sensitivity at the desired operating frequency is used as the objective value for optimization.

As the overview shown in fig. 1, genetic algorithm-based optimization involves encoding potential spring designs as some sets (chromosomes), with genes representing key parameters such as number of folds and beam dimensions. Through iterative generations of selection, crossover, and mutation, the algorithm refines these designs to maximize sensitivity while ensuring they meet our stringent criteria for fabrication resolution and dimensional constraints. By exploring a vast solution space and leveraging evolutionary principles, genetic algorithms yield the spring design with an optimal balance between structural and sensitivity requirements. This approach not only enhances the efficiency of design and optimization processes on MEMS but also contributes to the creation of safer and more sustainable solutions for complicated mechanical systems. The optimal design (fig. 2) has 4 springs where each one has 2 folds and the dimensions of beam element are indicated in Table 1.

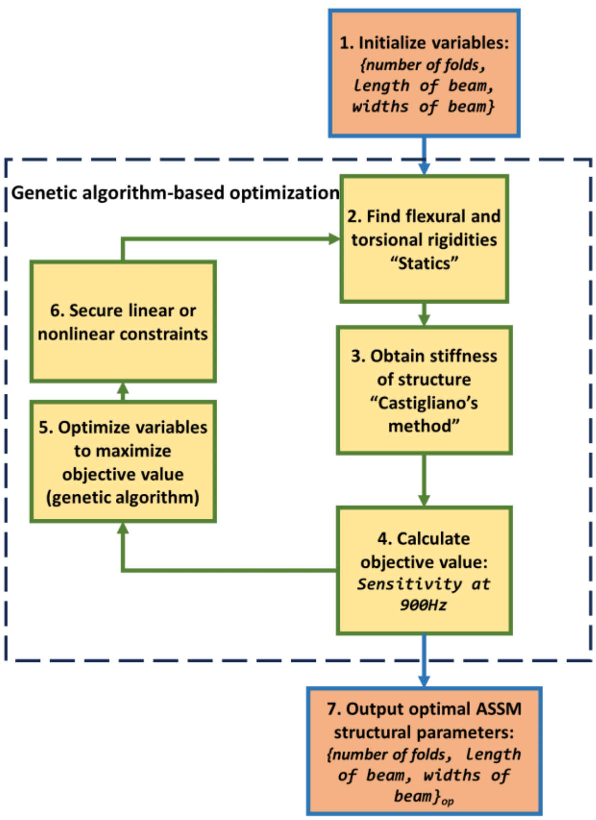

Figure 1 Overview of genetic algorithm-based optimization.

FABRICATION

The accelerometer was fabricated by the deposition and patterning of conductive layer, sacrificial layer, dielectric, and another conductive layer, respectively. The operation was preceded with an insulative layer of aluminum nitride to separate the wafer from the fabricated devices, the first conductive layer was deposited by sputtering aluminum layer which is then patterned with inductive conductive plasma. Then, the gap was formed by depositing a silicon oxide layer formed with plasma enhanced physical vapor deposition (PECVD). The dielectric selected for this operation is polyimide because of its triboelectric properties and process compatibility. The polyimide is patterned with CF4-O2 mixture of 15:45 sccm in reactive ion etchants. And then, another conductive layer is formed by sputtering and patterning aluminum again, the structure of the top electrode layer is shaped with serpentine springs to allow for the top and bottom layers to get in contact and release as the device is excited by a shaker later while testing. The fabrication process is concluded by dicing and releasing the pieces with vapor hydrofluoric acid etch of silicon oxide. The fabrication process is illustrated in fig.3. The schematic of the accelerometer and a 3D profile image of the released device are shown in fig.4 and the design parameters are shown in Table 1.

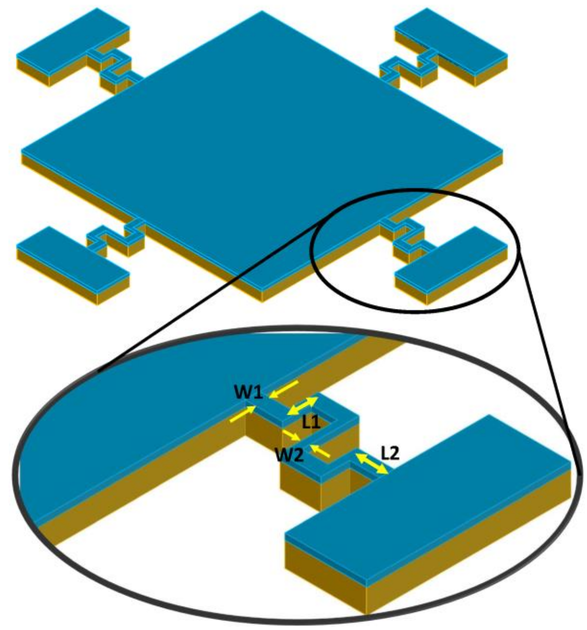

Figure 2 Schematic of optimal springs and proof mass on triboelectric accelerometer (blue: aluminum; yellow: polyimide).

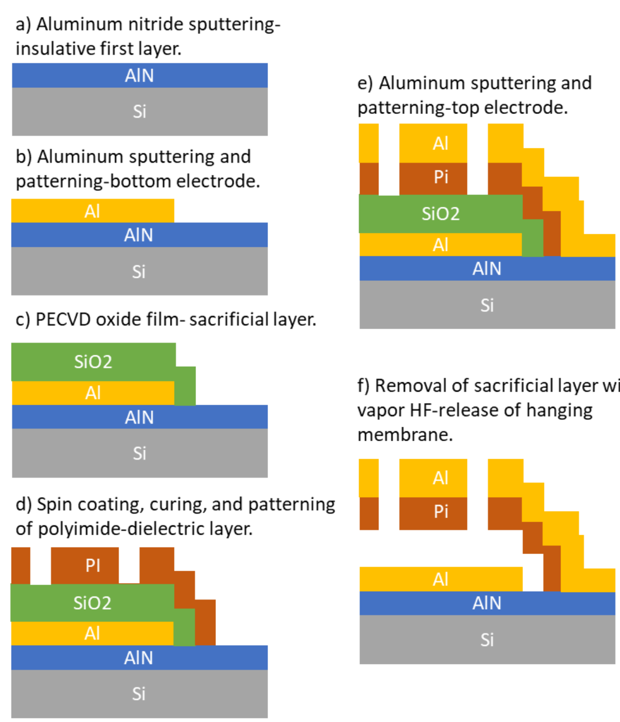

Figure 3 summary of the fabrication process.

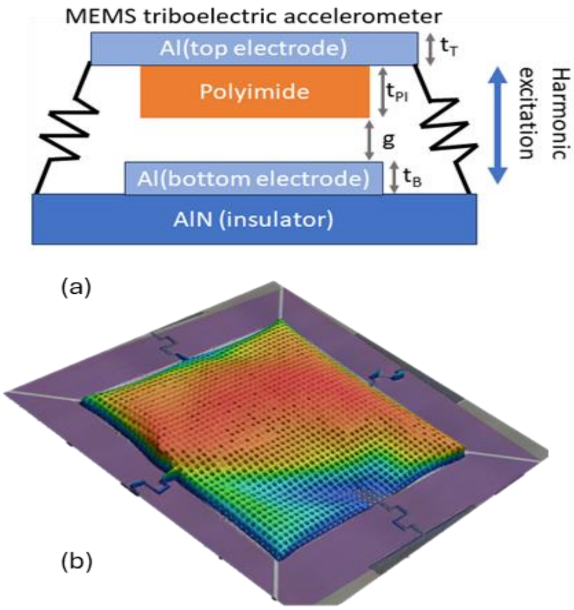

Figure 4 (a) Triboelectric accelerometer schematic, and (b) released accelerometer 3D profile.

Table 1: design parameters.

Parameter	description	Value
t_T	Top aluminum thickness	100 nm
T_{PI}	Polyimide thickness	4-5 µm
T_B	Bottom aluminum thickness	200 nm
g	Top-bottom gap	1 µm
L1	Beam length 1	70 µm
L2	Beam length 2	80 µm
W1	Beam width 1	35 µm
W2	Beam width 2	15 µm
n	Number of folds	2
A	Top electrode area	4 mm^2

EXPERIMENTAL SETUP

After fabricating the accelerometer, both conductive layers are connected to a printed circuit board by wire bonding. The device is placed on a mini electro dynamic shaker (B&K 4809) driven by an amplifier (B&K 2706) and controlled by a DAQ (USB-6366). The output voltage from the accelerometer is read by the DAQ and the input excitation acceleration is calculated from the measurement of the velocity which is done by laser doppler vibrometer (MSA500). The featured design of the accelerometer is expected to have its resonance at 900 Hz with maximum voltage ~1 V as the system is harmonically excited with 8 g at 1 kHz. The built experimental setup is capable of providing the required excitation accelerations at the testing bandwidth. It is done by variating the input voltage value and correlating it to the acceleration measured by the vibrometer prior to the actual testing with simple trial and error. The testing setup is shown in fig.5.

RESULTS

The fabricated MEMS accelerometer was tested at frequency bandwidth from 0.5 to 4 kHz with excitation amplitude ranging from 2g up to 10g with sinusoidal waves. Lower frequencies are hard to test using this setup due to the high current requirement of the electrodynamic shaker. The frequency response for the harmonic excitation is reported in fig.6. The frequency response shows a noticeable resonance peak at 1.25 kHz with 1.8 V generated at the highest end as a response to excitation of 10g. the frequency response for the rest of the tested bandwidth is relatively flat for every tested acceleration amplitude. The discrepancy between the expected (900 Hz) and the experimental resonance (1.25 kHz) stems from the residual stresses during deposition processes of spin-coating the polyimide and from the sputtering deposition of the aluminum layer. These stresses cause the released membranes to buckle up which creates undesired differences between the designed and the actual device.

Fig. 7 depicts the generated voltage against excitation amplitude, revealing the lowest sensitivity of 128.7 V/g at 500 Hz. At the resonance frequency of 1.25 kHz, the highest sensitivity of 186.5 mV/g was recorded. The recorded sensitivity values show improvement over a mechano-acoustic sensor, which had 76 mV/g sensitivity [13] and even over other MEMS triboelectric accelerometer made with Teflon and aluminum pair which had 43 mV/g over the same acceleration range [9]. Furthermore, the system also shows improvement when compared to the performance of our previous design which has 68.3 mV/g sensitivity with only 0.7 V as the highest produced voltage [10]. It is also noticed that there is a linear relationship between the measured acceleration and the produced voltage for the fabricated accelerometer at each frequency. Results present a promising design that can be suitable for self-powered MEMS motion sensors or microphones.

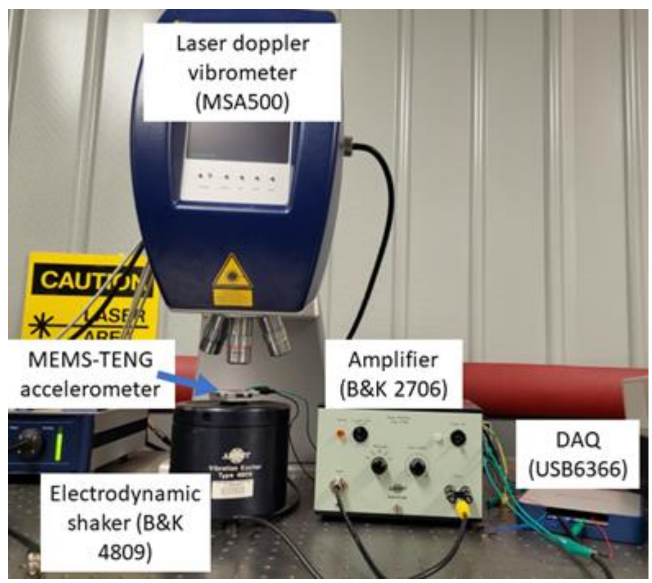

Figure 5 Testing setup.

CONCLUSION

In this work, we significantly enhanced the design of a triboelectric accelerometer by genetic algorithm and by modifying the fabrication process. We targeted maximum sensitivity in our optimization and changed the placement of the dielectric layer from the bottom to top. The changes made to the fabrication process alongside the changes in the design have improved the device output. In addition, the new process simplified the process by eliminating the usage of amorphous silicon which was used for creating proof-mass which was no longer needed because the polyimide layer on top acts both as a structural (proof mass) and a dielectric layer. The polyimide has low film stress compared to amorphous silicon which varies depending on deposition conditions and requires low deposition temperatures to guarantee good film quality. The resulting accelerometer also has the advantage of uniform flat response outside the resonance and a linear relationship between inputs and output voltage. These characteristics make the self-powered accelerometer an ideal sensor for various applications such as wearable breathing monitors.

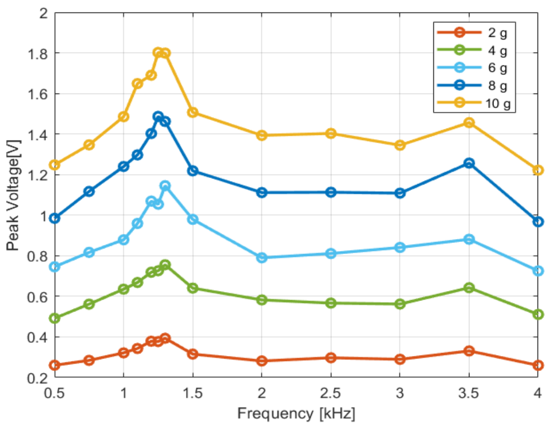

Figure 6 Frequency response of the accelerometer.

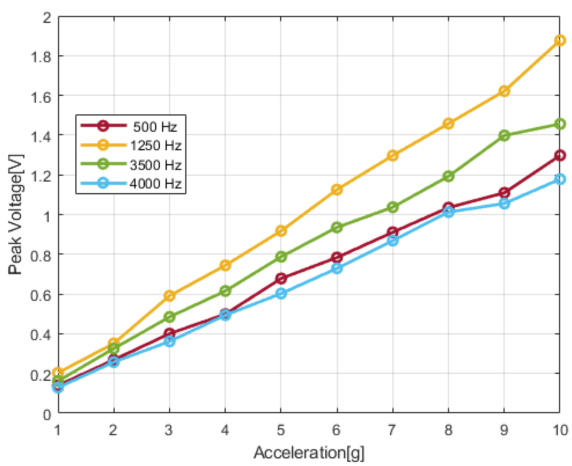

Figure 7 Acceleration-voltage relationship of the accelerometer.

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