Finite Element Modeling and Simulation of Piezoelectric Energy Harvesters Fabricated in CMOS Technology

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ABSTRACT

Here we present a micron scaled piezoelectric energy harvester fabricated in a commercial Complementary Metal Oxide Semiconductor (CMOS) technology. The device is a multilayer cantilever clamped on one end that utilizes interdigitated transducers (IDTs) to collect charge from a zinc oxide (ZnO) piezoelectric layer. Hence the cantilever beam operates in the d_{33} mode in order to produce more energy than a d_{31} structure. Finite element modeling and simulations are performed to analyze the voltage on the IDTs for various frequencies with and without the addition of a proof mass. The results presented demonstrate that commercial FEM software can help designers to determine parameters such as material thickness, proof mass, and IDT dimensions for novel piezoelectric energy harvester devices pre-fabrication.

Keywords: piezoelectric, zinc oxide, interdigitated transducers, finite element modeling, complementary metal oxide semiconductor

1 INTRODUCTION

Energy harvesters in microelectromechanical systems (MEMS) technology are gaining increased popularity as they enable self-powering based on simple ambient vibrations [1]. Unlike batteries with their finite power supplies, energy harvesting devices generate their own power and can extend the lifetime of electronic devices greatly. The small sizes and high power densities of MEMS energy harvesters are advantageous for powering of small electronic devices for wireless and biomedical applications.

There are several different types of energy harvesters with the most popular being piezoelectric transducers. Piezoelectric devices directly convert vibration energy to voltage since electrical charges are produced under mechanical loads. Unlike other energy harvesters such as electromagnetic and electrostatic transducers, piezoelectric devices do not require any extra components and complex geometries to function and can deliver relatively high output voltages. Electrostatic devices require an input voltage and electromagnetic devices may require transformers to meet applications with required voltages higher than approximately 2V [1].

Limited work has been completed in literature on piezoelectric energy harvesters employing IDT configuration. Therefore, the accuracy of FEM simulations is of paramount importance in determining design parameters and predicting post-fabrication performance metrics. Moreover, conventional designs focus on placing the IDTs on top of the piezoelectric layer whereas our configuration has the IDTs embedded within the ZnO layer as in Figure 1 in order to maximize collection of charges.

The most widely used technology in the current ASIC (application specific integrated circuit) industry is CMOS due to its low power, high performance, and high levels of integration capabilities. Furthering these compelling advantages in developing sophisticated electronic systems, recent developments in the areas of silicon micromachining and nanotechnology allow high precision fabrication methods for developing stand-alone intelligent systems with large scale integration capabilities.

Previously we reported on the details of fabricating CMOS compatible MEMS devices [2]. As demonstrated in this work, it is possible to produce high quality IDTs on silicon (Si) based CMOS microchips and use thin film fabrication methods to coat these chips with a piezoelectric material of choice. Figure 1 shows a cross sectional view of the conceptual model built to represent this fabrication sequence. FEM tools were used to translate this conceptual model into electromechanical simulation domain to characterize the performance of this energy harvester. Following sections summarize the results obtained in modal and harmonic analyses of the device.

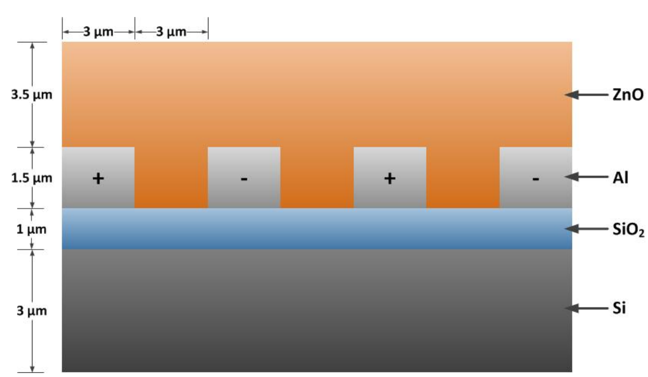


Figure 1: Cross sectional view of the side of the cantilever showing the alternating polarities of the IDTs.

2 MODEL

2.1 Motivation

The coupled equations that govern the piezoelectric device operation are given in a general form as follows:

$$S = s^E T + d^t E \quad , \quad D = dT + \epsilon^T E \qquad \text{(1a and 1b)}$$

where S is the strain, s^E is the compliance under a constant electric field, T is the stress, d is the piezoelectric constant matrix, the superscript t indicates the transpose, E is the electric field, D is the electric displacement, and ϵ^T is the permittivity under a constant stress field. The d_{33} piezoelectric constant, which is an element of d, is generally larger than the d_{31} constant, which is also an element of d. The '33' signifies that the polarization of the piezoelectric material is parallel to the stress along the 3-axis, shown in Figure 2(a), while the '31' indicates that the polarization is perpendicular to the stress with the polarization along the 3-axis and the stress along the 1-axis, shown in Figure 2(b). It was demonstrated by Sood et al. [3] and Jeon et al. [4] that a d_{33} mode piezoelectric generator harnesses higher voltage and power than a d_{31} mode of similar beam dimensions. The model presented is a piezoelectric beam utilizing IDTs in order to create a polarization in the d_{33} mode. For ZnO, the d_{33} constant is 1.167×10^{-11} C/N whereas the d_{31} constant is -5.43×10^{-12} C/N.

Assuming all of the piezoelectric material is poled in the d_{33} mode as in Figure 3(a), based on the theoretical analysis by Knight et al., the total electrical energy generated by a piezoelectric structure clamped on one end can be generalized as

$$U = \sum_{i=1}^{n} \left(\int_{L_i} \int_0^W \left(\sum_{j=1}^{m} \int_{H_j} dU_j dz \right) dy\, dx \right) \qquad (2)$$

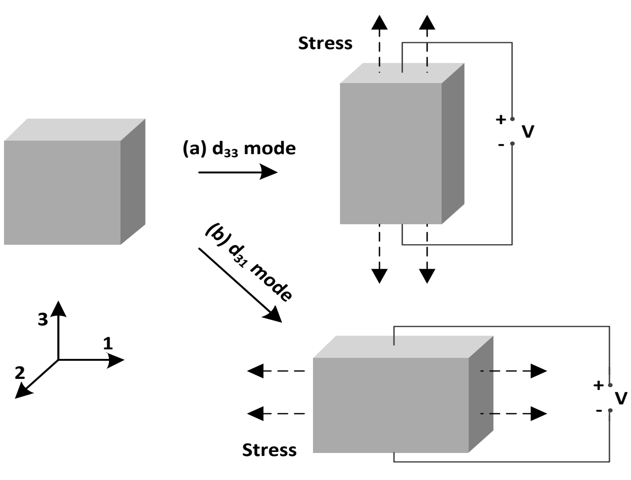
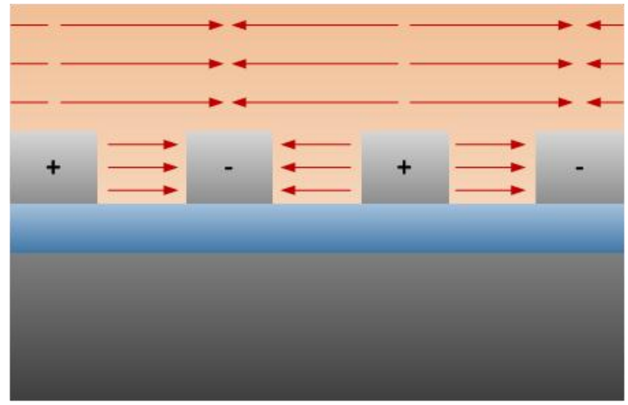
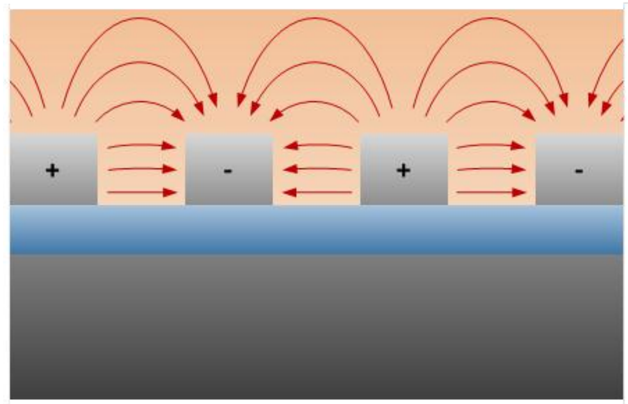


Figure 2: Diagram of operation principle of a piezoelectric material under stress in (a) d33 mode and (b) d31 mode.



(a)



(b)

Figure 3: Illustrations of (a) ideal poling in a d_{33} beam and (b) the non-uniform poling that exists around the electrodes.

where n is the number of sections between IDTs, L_i is the length of section i, W is the width of the cantilever, m is the number of layers of the cantilever, H_j is the height of layer j, and dU_j is the energy term for small volumes of layer j [5]. However, in reality the poling of the electric field under the IDTs is non-uniform as in Figure 3(b). Mo et al. [6] derived the total electrical energy generated by a piezoelectric device assuming the region is non-poled under an IDT. Capturing the exact energy generated by a piezoelectric device using analytical methods is challenging and hence FEM analysis is necessary to determine the characteristics of the device.

2.2 Construction of Model

The proposed energy harvester comprises four layers. As part of the CMOS fabrication process, Si is used for the bottom substrate. On top of the Si substrate is a layer of silicon dioxide (SiO_2) acting as a dielectric shielding between the Si substrate and the upper layers composed of aluminum (Al) and ZnO. The third layer is the set of IDTs made out of Al, which are embedded within the fourth layer of the piezoelectric ZnO as in Figure 1. The dimensions of the device can be seen in Figure 1 and Figure 4. By having

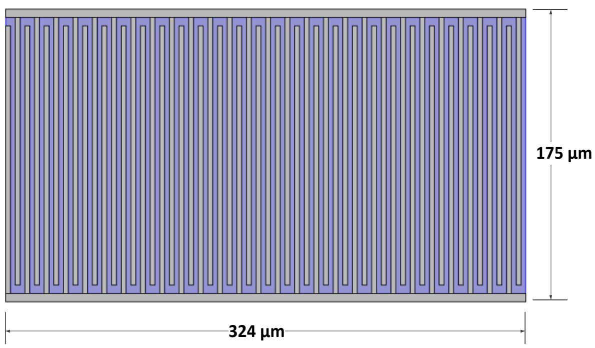


Figure 4: Top view of device along with the IDTs in grey.

the IDTs embedded within the ZnO, we expect to maximize the collection of charges on the IDTs due to the higher contact area between the electrodes and the piezoelectric layer.

3 SIMULATIONS AND DISCUSSIONS

3.1 Modal Analysis

A modal analysis of the device is imperative in determining the frequencies of operation. Through the FEM software COMSOL, the eigenfrequencies are found in Table 1. Because lower frequencies are desired for piezoelectric energy harvesters, we will focus on mode 1 for the rest of the analysis.

Mode	Eigenfrequency (kHz)
1	80.89
2	324.40
3	506.17
4	1061.01
5	1269.33

Table 1: Results of modal analysis.

3.2 Harmonic Analysis

Several studies are performed in the frequency domain in order to analyze the behavior of the piezoelectric energy harvester. Using the resulting eigenfrequency of mode 1 found in the modal analysis, a frequency sweep from 80 kHz to 81.4 kHz was performed with a step size of 0.2 kHz. A force of 0.5 µN was applied at the free end of the cantilever and no damping was used in the harmonic analysis. Not only was one set of IDTs grounded but also the bottom of the Si substrate was grounded in order to prevent the layer from electrically floating.

Voltage between two electrodes of the IDTs are measured from the device in the harmonic analysis. One of the electrodes used was ground as a reference for the voltage of the other electrode. Also, the electrode selected

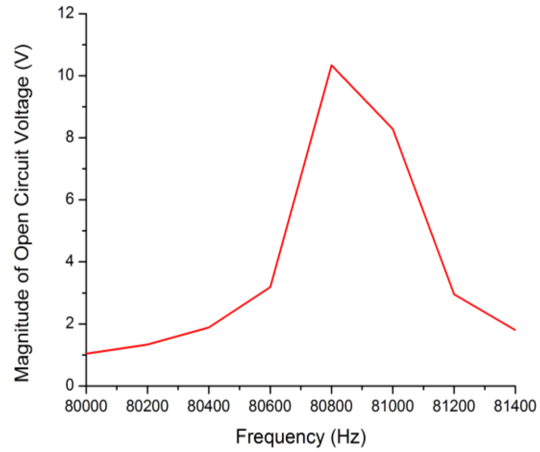


Figure 5: Frequency response of the voltage on the IDT.

for measuring the voltage was near the clamped end of the cantilever because most of the voltage produced is in that area due to the massive normal force pushing against the clamped end.

From Figure 5, the peak of the magnitude of the voltage occurs at 80.8 kHz. This verifies that the resonance frequency of the device is around the eigenfrequency of 80.89 kHz. The magnitude of the voltage at this point is 10.34 V.

3.3 Proof Mass

Addition of a proof mass is used to lower the frequency of operation for energy harvesters. However, it can also reduce the voltage generated by the device. Attached to the free end of the cantilever is a proof mass made of tungsten (W). The base of the proof mass has dimensions 75 µm x 75 µm. It is centered along the width of the cantilever. A parametric sweep on the height of the proof mass was performed along with modal and harmonic analyses for each step. By increasing the height, we are increasing the overall mass.

Evaluating only the eigenfrequency of the first mode for each step in the parametric sweep, a decrease in the eigenfrequency is evident in Figure 6 as the proof mass increases. As the mass increases, the rate of decrease of the eigenfrequency decays. This follows the theory that the eigenfrequency is inversely proportional to the square root of the overall mass [7]. Figure 7 illustrates how the voltage on the same electrode used in the harmonic analysis without a proof mass changes with addition of the proof mass. In general, the voltage decreases with increasing mass.

4 CONCLUSION

Through the FEM analysis of the proposed piezoelectric energy harvester, several characteristics of the device are explored in detail. The results follow the trends that were expected. Adding a proof mass and thereby increasing the

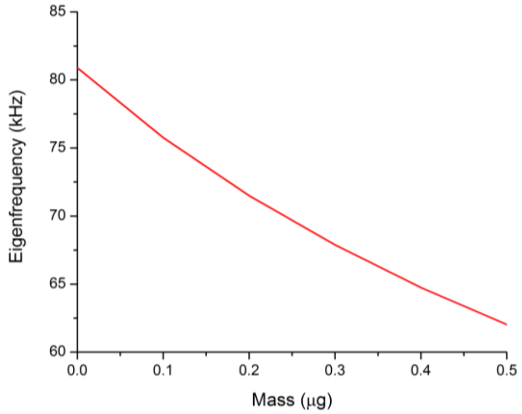


Figure 6: Relationship between the eigenfrequency of the first mode and the mass of the proof mass.

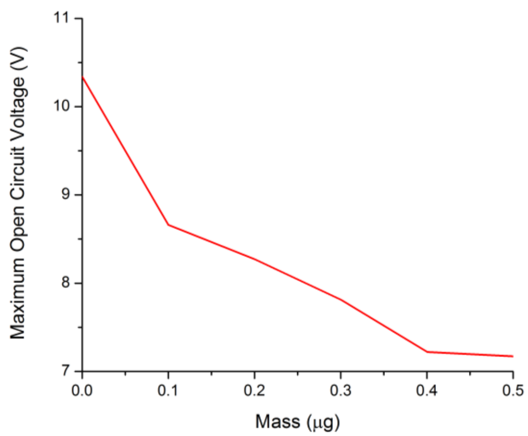


Figure 7: Relationship between the maximum voltage and the mass of the proof mass.

weight reduced the frequency of operation for the device. This is a necessity because lower frequencies allow for the device to be operational in a wider variety of practical applications. However, the voltage generated by the device does decrease, which is a cause of a smaller amount of stress throughout the ZnO layer. This will also affect the power output of the energy harvester adversely. Overall, it was seen that the energy harvester fabricated in CMOS technology can be modeled through FEM tools. This is significant in pre-fabrication study for designing energy harvesters in a simple and effective manner.

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