Design of MEMS Energy Harvester with Interdigitated Electrodes for Railway Tunnel Health Monitoring

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Abstract- Piezoelectric crystal has property to convert mechanical energy into electrical energy and vice versa. Electrode is used as primary device to harvest energy and converts mechanical vibrational energy to electrical energy due to piezoelectric phenomenon. Piezoelectric-type harvesters have the highest reported energy density per volume. The proposed work is concentrated onrecent energy harvester for self-powered Microsystems and proposes ZnO piezoelectric material for next generation harvesters. Design and simulation is done for interdigitated electrode for energy harvester. In this worksimulation is carried out to sense the vibrations induced in railway tunnels due to moving trains. Wireless sensor networks are used for tunnel maintenance. Energy harvesters can be used in these networksas an alternate source of power. IDEsenses vibrations due to moving trains, ranging from 200 to 350 Hz. The potential generated by harvester is 68 mVand the power is 0.028μW. ZnO can be flexibly used for the purpose of energy harvesting. Interdigitated electrode is chosen over parallel plate electrode due to better performance. Electrode is connected in d33 mode for coupling purpose.Cantilever for vibration sensor is made by ZnO as piezoelectric layer and Silicon as structural layer.These layers are separated by SiO_2.Further in fabrication, conventional photolithography is used along with lift off process for making aluminum electrode over cantilever beam.

Keywords: *Piezoelectric material, energy harvesting, MEMS.*

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I. INTRODUCTION

Railway tunnels are long and require maintenance. Themaintenancerequires sensation of cracks and inclination of tunnel walls that can be done by wireless sensor networks like inclinometer and crackmeters. These sensor networks are powered up by 0.2mW.Recent improvements in the microelectronic and micro-electromechanical system (MEMS) technologies enabled the fabrication of various sensors with remarkably small dimensions and low power requirements. These wireless sensor networks can monitor several parameters simultaneously. Although success of such systems heavily depends on the performance of the sensors, the major limiting factor is generally the power management usingthe simplicity of the design and fabrication. batteries. Currently used batteries increase the cost and the size of these devices. It is not feasible to replace or manually recharge them.

A possible solution to this problem is to apply a form of energy harvesting to convert the available ambient energy into electrical energy to recharge these batteries or substitute batteries. Interdigitated electrode can be used in these energy harvesters to sense the vibrations induced due to trains in tunnels. Energy harvester can be used effectively to power up wireless sensor networks and other networks in tunnels. This will benefit maintenance of these tunnels to make them safer.

Therefore, current interest is growing in utilizing harvested energy that is stored in on-chip capacitors and effectively eliminating the batteries. Although the ambient energy can be available in different forms, mechanical energy is widely preferred for energy harvesting applications because of Alternative sources of energy are solar, magnetic field and wind. Mechanical vibrations (300 _W/cm^3) and air flow (360 _W/cm^3) are the other most attractive alternatives. In addition to mechanical vibrations, stray magnetic fields that are generated by AC devices and propagate through earth, concrete, and most metals, including lead, can be the source of electric energy [1].

II.EXPERIMENTAL SECTION

A. *Energy Harvester*

In MEMS cantilever based energy harvester, mechanical energy is extracted by damping the motion of suspension proof masses within the devices. There are three main types of Mechanical energy harvesters: 1) piezoelectric,2) electromagnetic, and 3) electrostatic as shown in figure 1.b.Piezoelectric-type harvesters have the highest reported energy density per volume. Furthermore, piezoelectric materials have an inherent capability of converting the mechanical energy into electrical energy, eliminating the need for external magnetic fields, complicated switching systems, and architectural design complexities. Power can be generated from various

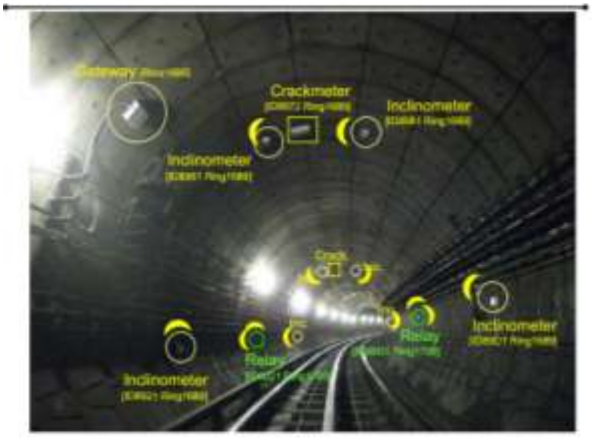


Figure 1. Wireless sensors locations in a tunnel by Prof. Kenichi Soga Professor of Civil Engineering Department of Engineering [10].

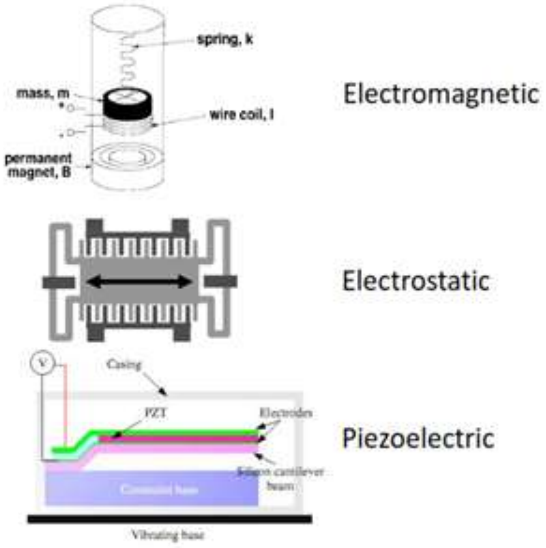


Figure 2. Different energy harvesters [2]

environmental sources such as ambient heat, light, acoustic noise, radio waves, and vibration [2]. Vibration energy harvesting is the most suitable power generation method because vibrations are readily available in almost all cases. A highly efficient way to harvest vibrational energy is to use piezoelectric materials for the energy transformation [3]. When base of structure is accelerated due to vibrating source(s), pressure (stress) is exerted to a material. This creates a strain or deformation in the material. The capability of the piezoelectric thin film in generating an electrical output in response to mechanical energy or vibration has given a significant impact in our daily lives. Piezoelectric thin film has been widely used in various MEMS applications such as surface acoustic wave (SAW) resonators, pressure sensors, biomedical and energy harvesting. In energy harvesting application, a piezoelectric energy micro-generator typically harvests mechanical energy or vibrations and converts it to electrical energy through piezoelectric effect. Different piezoelectric materials can affect the performance of the energy harvester due to different piezoelectric constants. Some examples of piezoelectric materials include lead zirconatetitanate (PZT), zinc oxide (ZnO) and aluminum nitrate (AlN)[4]. These parameters affect the mechanical and electrical parameters of the device.

B. Benefits of Energy Harvester using Piezoelectric phenomenon

Mechanical energy in cantilever is generated due to stress and strains produced in beam as a result of acceleration of environmental vibrations. Two types of electrodes are used in this study as vibration sensing electrodes. These are parallel plate electrode and interdigitated electrode. Cantilever structure helps in mechanical to electrical transduction[9]. EH are popular and penetrating in various applications due to diverse benefits: Long lasting operability, No chemical disposal,Cost saving, Safety, Maintenancefree, Inaccessible sites operability, Flexibility.It is observed that 90% of WSNs cannot be enabled without energy harvesting technologies (solar, thermal, vibrations).

C. Electrodes

Toprak et al.[2] worked to obtain optimized geometry of IDE and cantilever, including the piezoelectric and non-piezoelectric material for cantilever. Geometry with PZT thickness of 0.6 µm and an IDE consisting of 12 finger pairs gave Maximum output energy of 0.37 pJ for a 15-µN force. This energy is reduced to 1.5 fJ for 5 µm PZT thickness with 2 electrode finger pairs. Chidambaram et al.[3] The leakage current density of the IDE structure was measured to be about 4 orders of magnitude lower than that of the PPE structure.

The best figure of merit (FOM) of the IDE structures was 20% superior to that of the PPE structures while also having a voltage response that was ten times higher (12.9 mV/µ strain). The IDE lowers power loss inside the PZT for this kind of electrode. Since IDE show better outputs it became part of interest due to better efficiency.

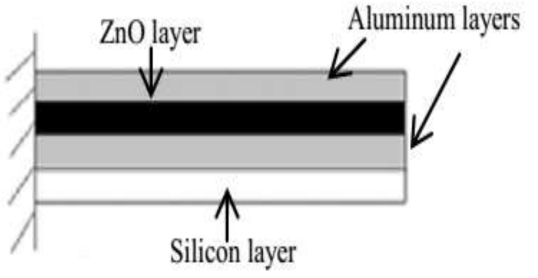


Figure 3.a. Parallel Plate Electrode (PPE)

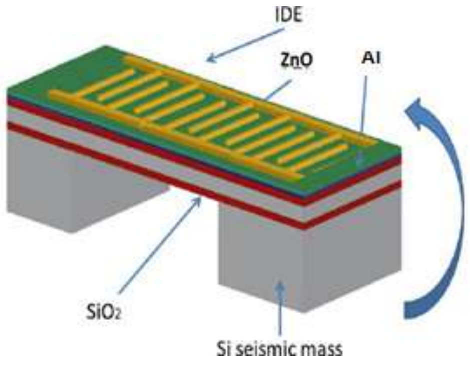


Figure 3.b. Interdigitated electrode

D. *Operating mode of ZnO beam*

A proper coupling mode is selected for this purpose. This involves two modes of operation. The first mode called 31 mode, involves the excited vibration force being applied perpendicular to the poling direction (pending beam). In the other modecalled 33 mode, the force is applied on the same side as the poling direction as shown in figure 4. The 31 mode is most commonly used. It produces a lower coupling coefficient 'k', when compared to the 33 mode[6]. Because of the opposite signs, the electric field created by d31-poled regions opposes the electric field created by the voltage on the electrodes. When the poling is not orthogonal under the electrodes, this opposing effect is reduced and a higher output charge is obtained [2].Zinc Oxide (ZnO) thin films on insulator-buffered silicon substrates with interdigitated electrodes (IDEs) have the potential to harvest more energy than parallel plate electrode (PPE) structures because the former exploit the longitudinal piezoelectric effect, which is about twice ashigh as the transverse piezoelectric effect used by PPE structures [3].Hence we can move further with IDE electrodes for energy harvester.

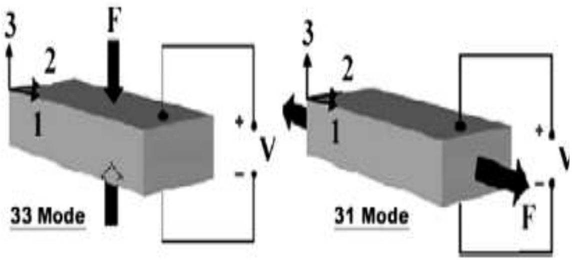


Figure 4. Operating Modes

E. *Material selection for Harwester:*

Most of the previous work has been concentrated on the material selection, coupling of electrode, figure of merit and their structural geometry. In case of interdigitated electrode the width, spacing and length of electrode fingers is also taken into consideration for optimization. Proper coupling mode improves power harvesting.Umi et al. [4], provided accurate information on the frequency, stress and voltage output of a ZnO piezoelectric energy harvester. They found out that ZnO piezoelectric energy harvester with the length of 150 µm, width 50 µm and thickness of 4 µm generates 9.9184 V electric potential under the resonance frequency of 0.71 MHz and 1µN/m2 mechanical force applied. This was a parallel plate electrode structure as shown in figure 3.a.

TABLE 1. Comparative performance of different piezoelectric materials. [6]

Piezoelectric materials	Displacement (µm)	Resonant frequency (MHz)	Electric potential
ZnO	5.85×10^{-9}	0.17	9.91
PZT	1.08×10^{-10}	0.15	9.01
AlN	8.66×10^{-11}	0.20	9.62

TABLE 2. Properties of chosen material

Properties	Density (kg/m^3)	Young`s Modulus (Pa)	Shear modulus (Pa)	Bulk modulus (Pa)	Poisson`s Ratio
Aluminum	2689	7E+10	2.59E+10	7.77E+10	0.35
Silicon	2330	1.85E+11	7.22E+10	1.40E+11	0.28

Silicon dioxide	2220	7.5E+10	3.20E +10	3.78E +10	0.18
Zinc Oxide	5860	8E+10	4.78E +10	1.42E +11	0.32

Table1.shows the effect of different piezoelectric material on output voltage, displacement and resonant frequency. The different values of output potential obtained are observed to be highest for ZnO.

F. *Basic Design Configuration*

Piezoelectric material deforms in the presence of electricfield and vice-versa. It produces electrical charge whenmechanically deformed.The piezoelectric constitutiveequation is defined as follows:

$$\delta = \frac{\sigma}{Y} + dE \qquad (1)$$

$$D = \varepsilon E + d\sigma \qquad (2)$$

Where δ = mechanical strain (µm/µm)

σ = mechanical stress (µN/µm^2)

Y = modulus of elasticity (Young Modulus) (µm^2/µN)

d = piezoelectric strain coefficient.

The modulus of elasticity (Y) affects the stiffness of the bender whereas a high dielectric constant (ε) lowers the source impedance and is preferable for energy harvesters.

G. *Analytical study*

In determining the resonance frequency of the cantilever beam during bending. Stoney's equation which relates cantilever end deflection δ to applied force σ is referred:$\delta = \frac{3\sigma(1-\gamma)}{E\left(\frac{L}{t}\right)^{\wedge}2}$ (3)

where*v* is Poisson's ratio, *E* is Young's Modulus, *L* is the cantilever's length and *t* is the cantilever's thickness.

The cantilever's spring constant, *k* can be expressed as

k=$\frac{3EI}{L^{\wedge}3}$(4)
where*I* is moment of inertia of the cantilever.

The equation of moment of inertia is given as

$$I = \frac{bh^{\wedge}3}{12} \qquad (5)$$

where*b* is width of the cantilever and *h* is the thickness.

In order to identify the resonant frequency, the following equation is referred.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (6)$$

where mass, *m=ρ.h.L.w*. In this case, *ρ* is the resistivity, *h* is the cantilever's height, *L* is the length of cantilever and *w* is the cantilever's width. It shows that the resonance frequency is afunction of spring constant and cantilever's mass.The AC output power calculated across 100 kΩ load resistor (R) by using formula:

$$\text{Power} = [V_{\text{Peak-peak}} / 2.828]^2/R \qquad (7)$$

III. RESULTS AND DISCUSSION

A. *Comparison between Parallel Plate Electrode (PPE) andInterdigitated Electrode (IDE)*

These two types of electrodes can equally sense vibrations. The analysis for PPE and IDE both with equal dimensions and for same frequency of 8 kHz is carried out. PPE generates potential approximately of 32mV and IDE gives potential approximately of 60mV. Thus voltage simulation value for PPE is half as that for IDE. This difference between generated potential is due to coupling modes d_{31} and d_{33}. PPE operates at d_{31} operation mode and IDE at d_{33} mode of operation.

TABLE3. Comparing PPE and IDE

Comparing	PPE	IDE
Dimensions	650x150x5µm	650x150x5µm
Potential	32mV	60mV
Operating mode	d_{31}	d_{33}

B. *Simulation of IDE for energy harvesting application*

To sense vibrations induced in tunnels due to trains, cantilever must have its natural frequency i.e. resonant frequency in the range 200Hz to 350 Hz. According to analytical calculations from (6) the dimensions of 3000x700x2 µm can sense vibrations of frequency 306 Hz. After simulation the result for resonant frequency at mode1 is obtained as 286 Hz. In this beam silicon and ZnOare separated by thin layer of SiO_2.

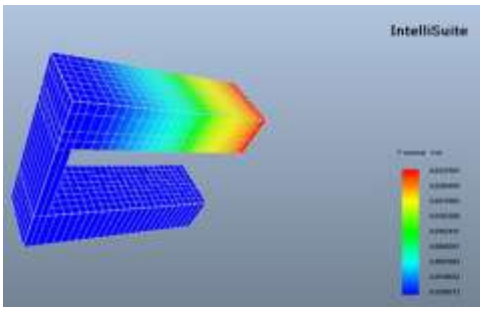


Figure 5.a. PPE dimensions 650x150x5µm (0.03275 Volts)

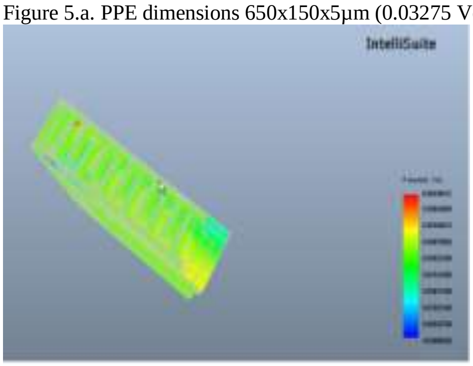


Figure 5.b. IDE dimensions 650x150x5µm (0.06039 Volts)

TABLE 4. Comparison of analytical and simulated values

Comparison	Analytical	Simulated
Displacement	2.02	4.73
Frequency (Hz)	306.454	286.485
Potential (mV)	62.67	68

IDE made from aluminum can collect the potential of 68.56 mV at the displacement of 4.73 nm. Considering equivalent value of stiffness constants for complete beam, the potential is obtained as 62.67 mV. Figure 5.a shows displacement i.e. deflection in z-direction and Fig 5.b shows value of potential generated in piezoelectric layer due to electric field formation along the thickness of beam. Comparison of analytical and simulated values is as shown in table 4.

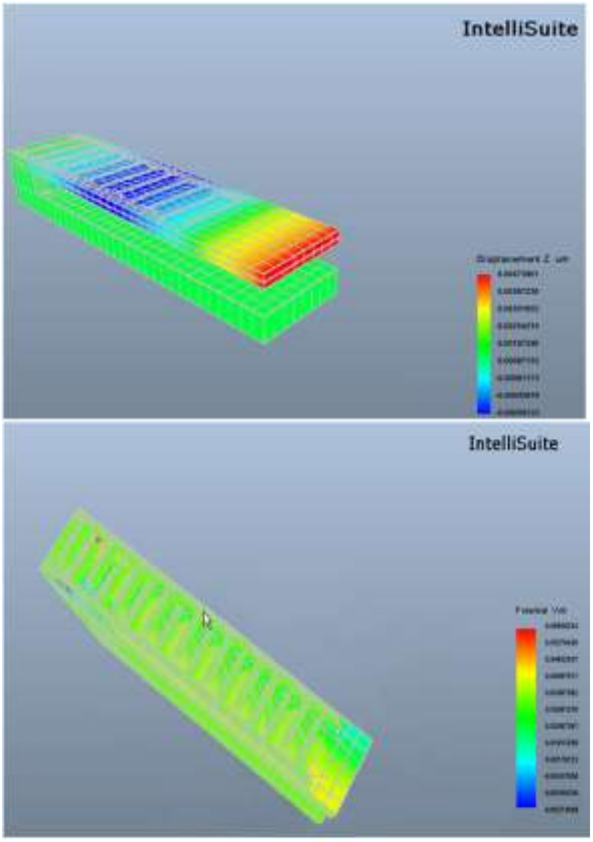
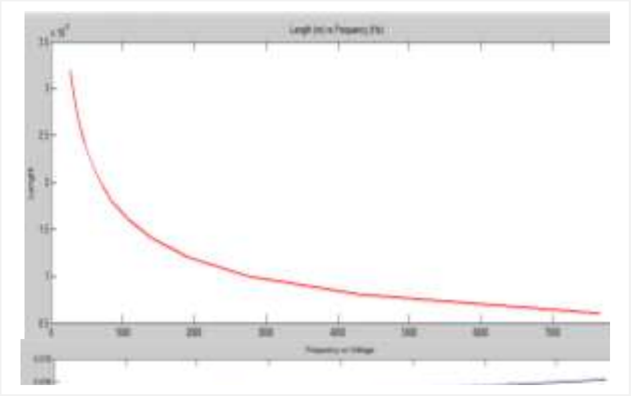
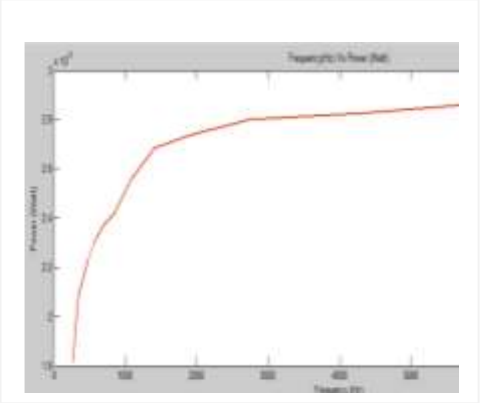


Figure 6.a. Displacement (µm); 6.b. Potential (volts).

C. *Graphical representation:length, frequency, displacement and power*

Keeping breadth and thickness constant, lengthvs frequency is calculated. For different lengths of cantilever beam for electrode, simulation was carried out for frequency. Plot shows that frequency decreases exponentially with increase in length and can help to decide the length of beam required for particular frequency.Simulated values of potential for obtained displacements are also plotted as shown in figure 7. Plot for potential with respect to displacement shows very less variation due to less thickness of beam.Electric field does not varies much in thickness of 2 µm as it depends more on thickness of piezoelectric material. Frequency verses power graph plot depends on potential as well as quality factor. Increase in frequency increases the power generation of individual electrode. Plot is approximately linear for power with respect to frequencies. Hence it is observed that the plot in figure 7. and figure 8 are nearly equal.





D. Performance Comparison with reported Energy Harvesters

Performance of devices with same kind of structures and functions can be compared by comparing their figure of merits (FOM). Figure of merit includes dimensions, output potential, frequency and quality factor into consideration.

$$\text{Here,Quality Factor } Q = \frac{f}{\Delta f};$$

$$\text{FOM} = \frac{Power}{Q.\,Volume}$$

TABLE 5. Performance comparison with reported Energy Harvester

Reference	Device	Dimensions	V_{peak}	Frequency(Hz)	FOM(V/m m^3.g
[17]	d31 PZT	2mmx0.6mmx 1.64µm	0.45	608	228.7
[18]	d31 PZT	2mmx3.2mmx 1.39µm	1.6	60	142.3
[19]	d33PZT	0.8mmx1mmx 10µm	2.2	528	705
[20]	d33PZT]	0.8mmx1.2mmx2µm	1.6	870	416
[21]	d33ZnO	2.5mmx0.5mmx2µm	1.05	485	1680
Proposed	d33ZnO	3mmx0.7mmx 2µm	0.136	286	2289

E. Array of electrodes

Figure 8 shows the array of five electrodes that yields potential of about 0.36 V. Now power requirement of the sensor networks is 0.2mWatt. Hence for 250µ Amps of current the 0.38 Volts gives the power generation of about 0.097 mWatt. Hence the array of 11 electrodes will be required to harvest energy equivalent to 0.209mWatt of power for sensor networks in tunnel.

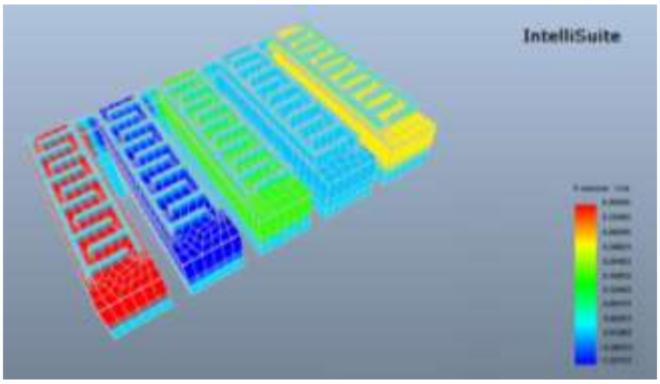


Figure 9. Array of five electrodes 3000x700x2µm.

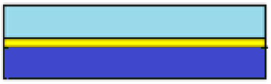
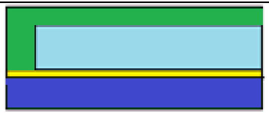
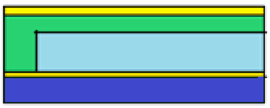
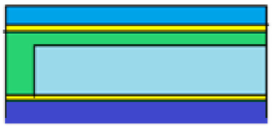
IV FABRICATION FLOW

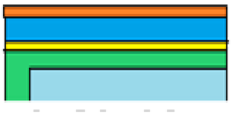
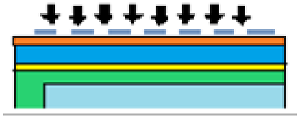
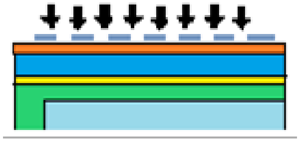
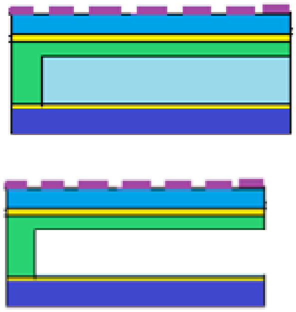
The material used for IDE is aluminum. The fabrication process started with n type <100> silicon wafer. Before undergoing oxidation process, silicon substrate undergoes normal cleaning process with RCA1 and RCA2 solution for removal of foreign substrate.

After oxidation, the surface of silicon oxide (SiO2) is deposited with Si_3N_4(LPCVD) which is furtherpatterned and etched.PECVD is the most widely accepted process for the deposition of SiO_2, Si_3N_4, BPSG and amorphous silicon films.Polysilicon structural layer deposition is done withthermal evaporation method. SiO_2 and ZnO is deposited through sputtering again. . The ZnO thin films can be deposited by various methods such as sol-gel [12], metalorganic chemical vapor deposition (MOCVD) [13], pulse laser deposition (PLD) [14], hydrothermal [15] and sputtering [16].

Among these sol-gel and RF sputtering methods are preferred. Unlike sol-gel, sputtering offers an advantage of single trial deposition to achieve desired thickness suitable in microfabrication and hence preferred in fabrication flow table 6. Lift-off process is used to make IDE electrode Thus after ZnO deposition negative photoresist is deposited and heat at 60 ^{0}C for 90 minutes. The heating process is known as soft bake. Softbake process is done to remove moisture on the surface of ZnO. UV light exposure is conducted for 10 sec to pattern transfer IDE mask on the surface of the sample. Development process is conducted for 15 sec. The sample is hard baked at 110^{0}C to remove unwanted moisture and improve the adhesion force in between layers. Now aluminium is deposited though sputtering process. Then resist is dissolved that removes unwanted material causing Lift-Off while dissolving photoresist.

Table 6. Fabrication Flow and Lift Off process for IDE

Step	Diagram	Step description
1		n type <100> silicon wafer cleaning process with RCA1 and RCA2
2		800 nm silicon dioxide is grown using thermal oxidation
3		Silicon Nitride is deposited using LPCVD.
4	 	Silicon nitride is patterned and etched using Buffered HF (Phosphoric acid). Polysilicon is deposited using thermal oxidation.
5		SiO_2 is deposited by PECVD process
6		The ZnO thin films deposited by RF-sputtering method.

Step	Lift-Off diagram	Steps
7		Negative photo resist is deposited and heat at 60^{0}C for 90 min.
8		UV light exposure to pattern transfer IDE mask.
9		Negative photo resist SU-8 is stripped out using cyclopentanone. C_5H_8O. And aluminum is deposited using Thermal evaporation.
10		Dissolving removes SU-8 and aluminum above photo resist also gets removed causing Lift-Off. At last sacrificial layer is etched out using BHF.

IV. CONCLUSIONS

Comparing IDE and PPE structures for electrodes it is observed that IDE has two times better output as compared to PPE. Zinc oxide material for next generation harvester is proposed as piezoelectric layer because of its excellence bonding to substrate material such silicon and high piezoelectric coupling coefficient. Cantilever beam with dimensions of 3000x700x2 µm yields potential of 62 mV and power of 0.0196 µW at frequency of 286 Hz. Thus to make this device applicable in wireless sensor networks, an array of IDE electrodes with enough potential is required to be used. Observing all the values of figure of merits in table 5, it is seen that the proposed device has better performance with FOM 2289. Thus, designing a proper d33 unimorph or bimorph device will increase energy harvesting performance. These structures are being used for wireless sensor networks. Still there is scope for further optimization to obtain power which will be enough to drive portable devices.

Wireless sensors used for structural monitoring requires 0.02mW. Thus arrays of 11 electrodes are needed that can generate potential of 0.209 mWattenough to powercrackmeter and inclinometer sensor networks. Also the performance of electrode can be improved by further optimizing dimensions of electrode.

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