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Piezoelectric MEMS to Harvest Energy from Ambient Vibrations

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Abstract— **Piezoelectric effect helps to convert ambient vibrations into electrical energy that can be used to power any electronic circuits. Electrode is used as primary sensor to sense these environmental vibrations to harvest energy and convert it to mechanical vibrational energy to electrical energy due to piezoelectric phenomenon. Energy density per volume for Piezoelectric-type harvesters is very high. The proposed work is concentrated on recent energy harvester for self-powered Microsystems and proposes ZnO piezoelectric material for next generation harvesters. In this work simulation is carried out on interdigitated electrodes to sense the vibrations in the environment for the frequencies of 170 to 350 Hz. Energy harvesters can be used in these wireless sensor networks as an alternate source of power. 68mV of potential generated by energy harvester and the power generated is 0.028µW. ZnO is a piezoelectric material that is 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. Structural layer is made by Silicon, piezoelectric layer is made by ZnO for the cantilever beam which senses vibrations. Structural layer and piezoelectric layers are separated by SiO2.For fabrication; conventional photolithography and lift off process are used for making aluminum electrode over cantilever beam.**

Keywords— Piezoelectric material, energy harvesting, MEMS.

I. INTRODUCTION

In recent years wireless sensor network technology has been widely used in environmental monitoring, health care, urban temperature detection, agricultural production and other fields. The main power supply for these wireless sensor networks still majorly relies on chemical battery, which offers limited energy storage. 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 using the 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 in environment. Energy harvester can be used effectively to power up wireless sensor networks.

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/cm3) and air flow (360_W/cm3) 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].

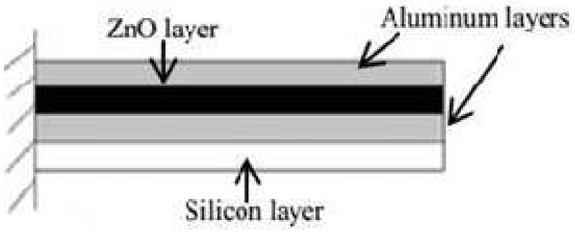


Fig.1. Parallel plate Electrode

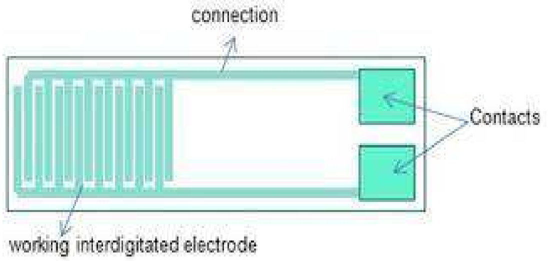


Fig.2. Interdigitated Electrode

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 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 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, Maintenance free, 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 **f**J 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 Fig.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 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.

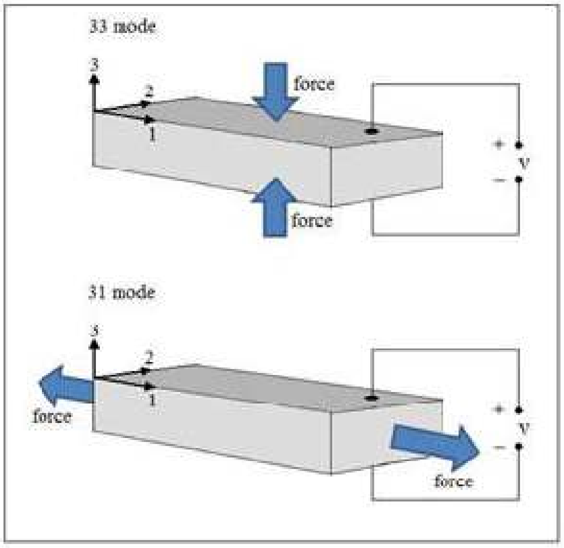


Fig.3 Operating modes

D. Material Selection For Harvester:

Most of the previous work has been concentrated on the material selection, coupling of electrode, Fig.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 Fig.1.

Piezoelectric materials	Displacement (µm)	Resonant frequency (MHz)	Electric potential
ZnO	5.85x10-9	0.17	9.91
PZT	1.08x10-10	0.15	9.01
AlN	8.66x10-11	0.20	9.62

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 d31 and d33. PPE operates at d31 operation mode and IDE at d33 mode of operation.

TABLE II. COMPARING PPE AND IDE

Comparing	PPE	IDE
Dimensions	650x150x5µm	650x150x5µm
Potential	32mV	60mV

B. Simulation of IDE for energy harvesting application.

In the range 200Hz to 350 Hz according to analy
om (6) the dimensions of 3000x700x2 µm can ser
equency 306 Hz. After simulation the result for reso
ode1 is obtained as 286 Hz. In this beam silico
parated by the layer of SiO2.

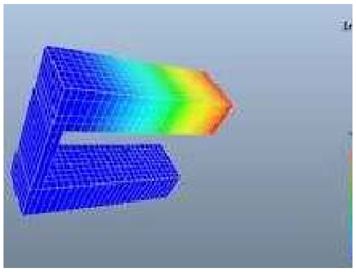


Fig.4.a. PPE dimensions 650x150x5µm (0.03275 Volts

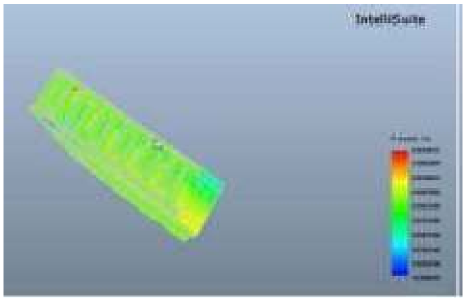


Fig.4.b. IDE dimensions 650x150x5µm (0.06039 Volts

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. Fig.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 III.TABLE III

COMPARISON OF ANALYTICAL AND SIMULATED VALUES

Comparing	Analytical	Simulated
Dimensions	2.02	4.73
Potential	306.454	286.485
Operating mode	62.67	68

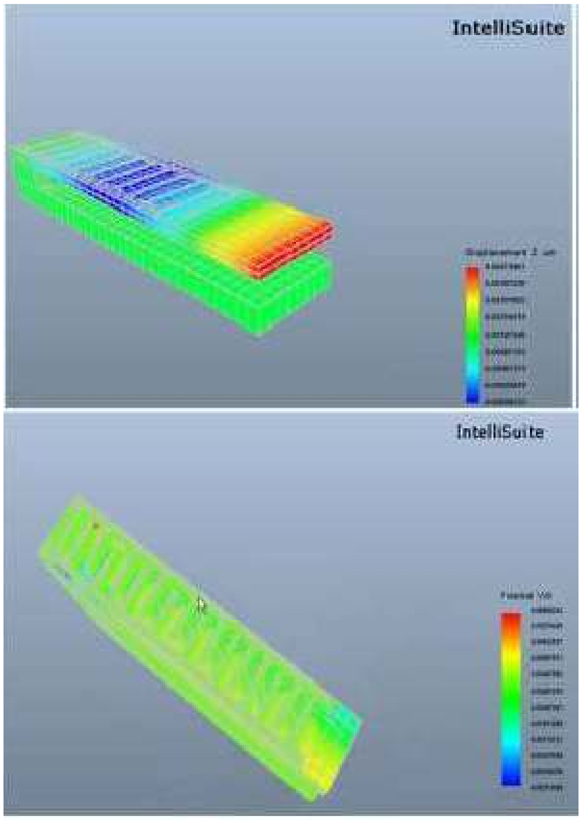


Fig.5.a. Displacement (µm); 5.b. Potential (volts).

C. Performance Comparison with reported Energy Harvesters

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

TABLE IV.

PERFORMANCE COMPARISON WITH REPORTED ENERGY HARVESTER

Reference	Device	Dimensions	Vpeak	Frequency(Hz)	FOM(V/m m3.g
[17]	d31 PZT	2mmx0.6 mmx 1.64µm	0.45	608	228.7
[18]	d31 PZT	2mmx3.2 mmx 1.39µm	1.6	60	142.3
[19]	d33PZT	0.8mmx1 mmx 10µm	2.2	528	705
[20]	d33PZT]	0.8mmx1.2mmx2µm	1.6	870	416
[21]	d33 ZnO	2.5mmx0.5mmx2µm	1.05	485	1680
Proposed	d33 ZnO	3mmx0.7 mmx 2µm	0.136	286	2289

D. Array of electrodes

Fig.6 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.

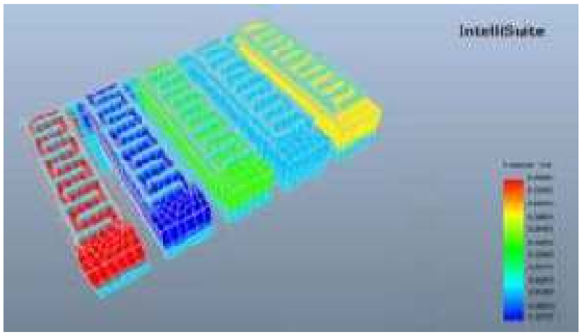


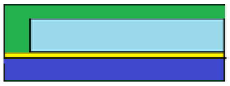
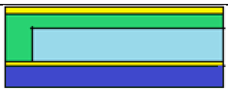
Fig.6. Array of five electrodes 3000x700x2µm.

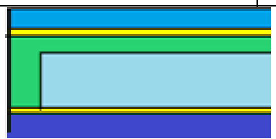
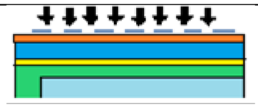
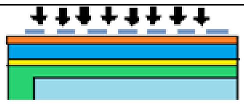
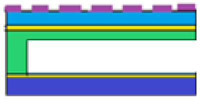
IV. FABRICATION FLOW

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 (SiO_2) 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 0C 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 1100C 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 V. 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 Silicon Nitride is deposited using LPCVD.
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		SiO2 is deposited by PECVD

		process
6		The ZnO thin films deposited
Step	Lift-Off diagram	Steps
7		Negative photo resist is deposited and heat at 600C for 90 min.
8		UV light exposure to pattern transfer IDE mask.
9		Negative photo resist SU-8 is stripped out using cyclopentanone. C5H8O. And aluminum is deposited using Thermal evaporation.
10	 	At last sacrificial layer is etched out using BHF.

V. CONCLUSIONS

Observing comparison in between IDE and PPE we see that Output of IDE is twice as better as compared to PPE. 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. The Fig.of merit that is obtained is 2289. 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. Also the performance of electrode can be improved by further optimizing dimensions of electrode.

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