A study of Energy harvesting process of MEMS piezoelectric pressure sensor

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***Abstract*— accurate measurement of pressure is a matured application of MEMS pressure sensor. But the self powered sensor is desirable one without compromising the sensitivity and to enhance energy scavenging credibility at the same conditions. Now piezoelectric materials are being used to harvest ambient energy. In this paper, the square shaped diaphragm based sensor has been designed and simulated to explore the energy generation capability as well as the sensitivity of the sensor using finite element software INTELLISUITE. The analysis shows that the deflection of the diaphragm is in a linear relationship with pressure applied. Also the thickness variation of the diaphragm as well as the piezoelectric layer is done to study its effect on the performance of MEMS piezoelectric pressure sensor.**

Keywords- Intellisuite; Energy harvesting; MEM ; Piezoelectric pressure sensor

I. INTRODUCTION

Pressure Sensors are one among the widely used micro sensors, mainly to sense pressure observed from gas flow, liquid flow, humidity etc. [1] The property of Piezoelectricity in piezoelectric materials causes generation of voltage on application of stress leading to change in polarization depending upon the two famous phenomenon as direct and indirect piezoelectricity. The mechanical deformation thus caused in the diaphragm is commonly sensed by piezoelectric methods which are having more advantageous in terms of external power supply [2, 3].

Though capacitive sensors have the advantage of greater pressure sensitivity and decreased temperature sensitivity. Despite that, piezoelectric sensors are the one due to its advantages such as excellent linear input-output relationship, small size, large dynamic range, easy integration with electronics and enabling self powered sensor [4].The geometry of sensing element depends upon techniques which occupy lesser area, enable easier lithography and fabrication[4,5]. With comparison to other type of pressure sensors such as capacitive, piezoresistive, the piezoelectric pressure sensor is suitable one in terms of energy requirements as well as for measuring dynamic pressure response.

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Because piezoelectric materials only respond to changing strains with different cantilever structures efficiently. [6, 7,10] S. Mohhamadi et.al describes analytical optimization of circular diaphragm based sensor structures with different boundary conditions leading to improved energy harvesters models provided mathematically[3].

William et. al [8] developed the generic model, where energy can be harvested from piezoelectric materials by comparing the second order control systems which basically provides the mechanical energy, also defined as the kinetic energy. The electrical equivalent circuit provides relative amount of electrical energy, where charge density and voltage generation according to load on the surface of the piezoelectric layer can be realized [9].

MO, Wright et. al [11, 12] demonstrated the pressure fluctuating systems, where circular diaphragm based energy harvesters have been employed to power up systems. It basically updates changes of voltage generated on the surface of the piezoelectric layer with respect to fluctuation of applied pressure and also implemented in piezoelectric actuation methods.

Otmann and Hoffman et. al [14,15] describes an approach to harvesting electrical energy from a mechanically excited piezoelectric element. By employing the capacitive impedance, mechanical vibration of varying amplitude can be harvested into energy. For optimal power flow purpose, an “energy harvesting” circuit is proposed which consists of an ac–dc rectifier with an output capacitor, an electrochemical battery, and a switch-mode dc–dc converter that controls the energy flow into the battery. Along with, adaptive control technique for the dc–dc converter is used to continuously implement the optimal power transfer theory and maximize the power stored by the battery.

Sodano, Inman et al [15] developed a PZT model for harvesting energy from structural sensors on a bridge or global positioning service (GPS) tracking devices. They established an experimental method to calculate charge accumulated on the surface of the PZT layer under applied strain. This model in turn simplifies design procedure necessary for determining the appropriate size and vibration levels which is necessary for accurate sufficient energy to be produced and supplied to the electronic devices.

In this paper, the designed MEMS piezoelectric pressure sensor consists of three components i.e. a squared shaped diaphragm and underneath the diaphragm, two cantilever PZT beams are integrated as shown in the figure 1 and the silicon substrate to act as base for the pressure sensor. The sensitivity and voltage generation capability of the piezoelectric sensor are studied to optimize performance.

Section I describes piezoelectric materials properties and its energy generation capacities, section II describes mechanical and electrical analysis of MEMS piezoelectric EH. Section III describes operating principles behind the proposed model. Section IV describes modeling of MEMS sensor and its respective analysis and section V describes the conclusions of this paper.

A. The piezoelectric cantilever configuration

There are two types of piezoelectric materials such as piezoceramics like Lead Zirconate Titanate (PZT) and piezopolymers such as polyvinylidene fluoride (PVDF). When piezoelectric materials are deformed or stressed, voltage appears across the materials. The mechanical and electrical behavior of these materials can be modeled by two constitutive equations [7].

$$S = s^{E} T + d_{t} E \quad (1)$$

$$D = d_{t} T + e^{T} E \quad (2)$$

Where S-mechanical strain , T-applied mechanical stress, E-electric field, D-electric displacement, s^E-matrix of elasticity under conditions of constant electric field, d-piezoelectric coefficient matrix, e^E-permittivity matrix at constant mechanical strain. A cantilever model is used in two different modes as 33 modes and 31 modes.

In 33 mode, voltage is generated in 3 directions, parallel to the direction of applied force which is called as compressive force.

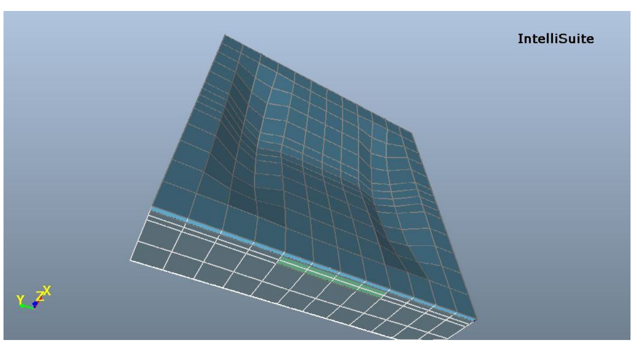

Fig .1: deformed shape of the sensor

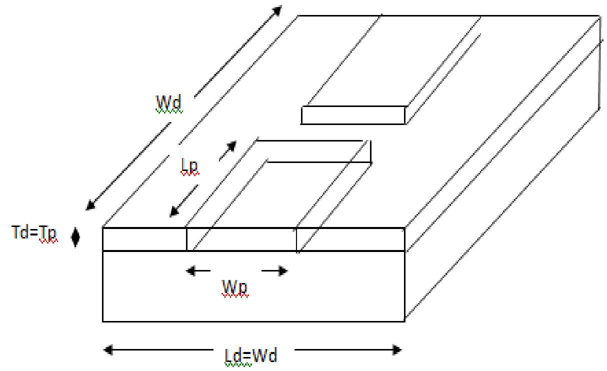

Fig .2: Dimension of sensor structure

In 31 mode, voltage is generated in 1 direction, perpendicular to the direction of applied force which is called as transverse mode. In this paper the 31 mode will be used for voltage generation purpose.

II. PIEZOELECTRIC ENERGY HARVESTERS MODELLING

A. Mechanical analysis

Williams and Yates [8] developed this generic model and It is a second order dynamic system which relates the input vibrations y(t) to the output displacement z(t).
Using the D'Alembert's law, the dynamic equation is given as:

$$m\frac{d^2z}{dt^2} + b\frac{dz}{dt} + kz = -m\frac{d^2y}{dt^2} \quad (3)$$

Where m- mass, b- damping coefficient, k- spring constant.
When there is damping on the system, due to the damper, there is net transfer of mechanical power into electrical power.

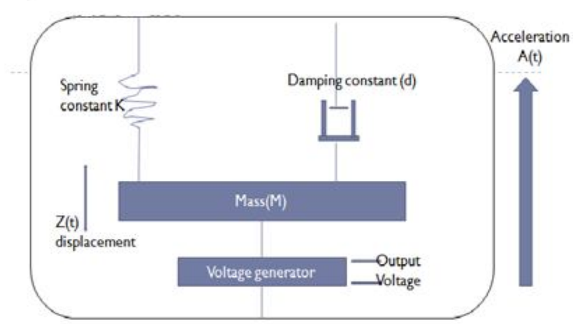

Fig 3. Generic model of PVEH

For sinusoidal excitation as

$$y(t) = Y \sin \omega t$$

The generated power is considered as

$$p(w) = \frac{m\varsigma_T Y^2 (\frac{w}{w_r})^3 \omega^3}{(1-(\frac{\omega}{\omega_r})^2)^2 + (2\varsigma_r \frac{\omega}{\omega_r})^2} \quad (4)$$

At resonant frequency, the power harvested from the model is maximum and is defined as

$$P = \frac{ma^2}{8\omega_r}.Q = \frac{F.a}{8\omega_r}Q \quad (5)$$

Where $a = Y\omega^2$, Q is the acceleration applied and quality factor of the piezoelectric material respectively.

From (5), it is observed that the power harvested is proportional to the force applied and quality factor of the model and also inversely proportional to the resonant frequency the cantilever beam. Therefore low resonant frequency of the cantilever is preferable for higher energy production.

B. Electrical Equivalent circuit of PVEH

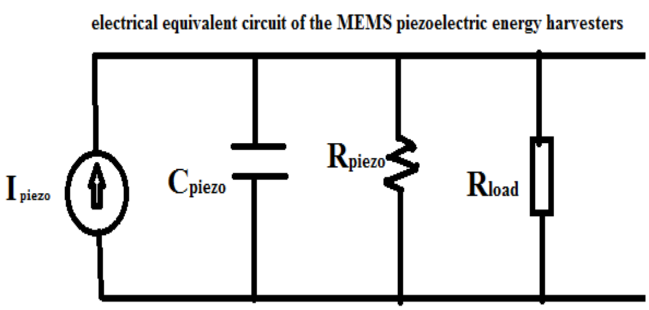

Fig 4. Electrical equivalent circuit of PVEH

The respective force equilibrium dynamic model can be transformed into the electrical circuit by using the **force-voltage analogy** shown in figure 4.

The harvester now can be represented as follows

$$-ma(s) = s.Z(s)(ms + b + \frac{k}{s}) \quad (6)$$

It can be written as by employing the duality nature as follows

$$-I(s) = E(s)(sC + \frac{1}{R} + \frac{1}{sL}) \quad (7)$$

Where I(s)=ma(s) , E(s)=sZ(s), C=m, $b = \frac{1}{R}$, $L = \frac{1}{k}$

At resonance the current source is equal to $I_{piezo} = mA\omega^2{}_n$ and since the harvester effective impedance is of capacitive type, so the input impedance is shown as

$$Z_i = \frac{1}{\omega_n C_{piezo}} \quad (8)$$

Therefore according to the power transfer theorem, the maximum power is harvested, when the load impedance will be equal to the internal impedance Z_i .i.e.

$$Z_{load} = Z_{input} \quad (9)$$

To store the electrical energy in a capacitor, it is given as

$$W(t) = \frac{1}{2}CV(t)^2 \quad (10)$$

Where W (t) is the stored energy at instant of time t. and voltage is the measured voltage across the capacitor.

Since the charge density is accumulated on the surface of the piezoelectric layer and voltage is generated across it due to its capacitive effect. The total theoretical energy generated by the harvester can be modeled as

$$E = \frac{1}{2}QV \quad (11)$$

Where E –the energy generated, Q- the charge density of piezoelectric layer and the V is the voltage generated.

$$Q = \rho AT \quad (12)$$

Where A is the area of the charge accumulated and T is the thickness of the layer and ρ is the charge density of piezoelectric layer

III. OPERATING PRINCIPLES OF PROPOSED MODEL

The diaphragm of the sensor as shown in figure (1) is poled as sensing layer at the top of the structure. The squared shaped diaphragm due to its boundary conditions with all edges fixed, on applying uniform pressure loading undergoes deformation at the centre and in turn it will bend the piezoelectric cantilever beam attached at bottom layer beneath it. Since piezoelectric material due to its property will induce charge on its surface i.e. voltage perpendicular to the PZT layer. This is further enhancing the sensitivity of sensor defined as voltage with respect to applied pressure.

With square diaphragm of length L_d and thickness T_d the maximum stress at the centre of the each edge is written as

$$\sigma_{max} = \frac{.308PL_d^2}{T_d^2} \quad (13)$$

And the maximum deflection of the diaphragm at the center of applied load is written as

$$w_{\max} = -\frac{.0138PL_d^4}{YT_d^3} \tag{14}$$

The stress at the center of the diaphragm is written as

$$\sigma = \frac{6P(m+1)L_d^2}{47mT_d^2} \tag{15}$$

Where $m = \frac{1}{\nu}$ and ν is Poisson's ratio.

Due its applied pressure load, bending occurs at the cantilever beam attached therewith, which in turn produces strain perpendicular to the stress direction is written as

$$\sigma_{\max} = \frac{MT_p}{2I_p} \tag{16}$$

Where $\sigma_{\max}$ is the stress at piezolayer surface and M is the bending moment of the piezoelectric cantilever beam, t_p is the thickness of the piezolayer; I_p is the area moment of inertia with respect to the applied pressure load point.

Therefore the voltage generated in the piezolayer with strain produced if the mechanical shear stress in axis 3 is neglected as given as

$$s = d_{31}\frac{V}{T_p} \tag{17}$$

Where s is the strain along the axis 3, d_{31} is the piezoelectric strain coefficient, V is the voltage generated, t_p is the thickness of the piezolayer.

From (1-17) it can be derived that voltage and charge density will be affected as the load on the diaphragm will be applied. Since, voltage is directly proportional to the strain at the cantilever beam, therefore with increasing of applied load (until burst load), more amount of voltage will be obtained. So reasonable amount of energy can be harvested.

Since both parameters depend on the thickness of the diaphragm and the piezoelectric layer. So to observe better performance, optimization of the sensor is desirable.

IV. MEMS SENSOR MODELING

The sensor is designed with INTELLISUITE software 8.6 versions. The structure of the sensor consists of three materials as shown in figure (2), the substrate is of the silicon bulk material and the diaphragm is made up of Aluminium bulk material. Underneath the diaphragm, the piezoelectric layer is sandwiched at both side of the squared shaped substrate such that the pressure applied at the center produces more deflection at the center of the diaphragm in turn produces more strain in the cantilever beam sandwiched at next level.

Since the optimized result is dependent on the thickness of the piezoelectric layer as well as the diaphragm. The dimensions of different layers of TABLE 2 are taken as reference for simulation such that the variation of the voltage generated on the piezoelectric layer is described in section IV. The length, thickness and width of the layers are tabulated in TABLE 2.

TABLE 1: MATERIAL PROPERTIES OF DESIGNED SENSOR

Layers	Density gm/cm^3	Young's modulus (GPa)	Poisson's ratio	Piezoelectric coefficient (d311,d322,d333)
Si substrate	2.3	170	.26	
PZT(Lead Zirconate Titanate)	7.50	10000	.226	-.0001,-.0001,.0003
Bulk Al	2.7	70	.36	

TABLE 2: DIMENSIONS OF THE SENSOR STRUCTURE

Layers	Length(um)	Thickness(um)	Width (um)
Si substrate	120	20	120
PZT(Lead Zirconate Titanate)	55	1	30
Bulk Al	120	1	120

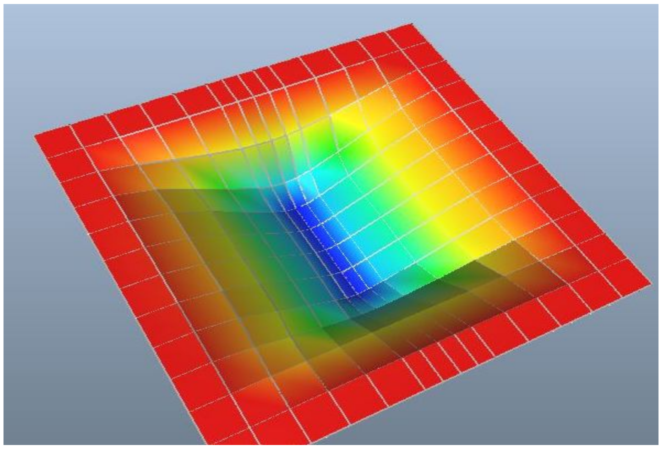

Fig .3: the shape of diaphragm at 1 MPa at scale of 1000.

Due to its structure, as the pressure is applied on the diaphragm, the deflection is along the length of the piezoelectric layer as shown in Fig.3.The mechanical conditions are done by making bottom surface of the structure, vertical faces of diaphragm as fixed constraint as boundary conditions and all the other surfaces are left as unconstrained.

V. RESULTS AND DISCUSSIONS

According to the analytical formulation, deflection of the diaphragm is directly proportional to the pressure applied at the center. So pressure–displacement analysis is done on structure of reference sensor dimension as mentioned in TABLE 2 is displayed in fig 4. A better linear relationship between them has been observed, which is suitable for improved linear sensitivity.

Since the pressure at the centre of the diaphragm will produce strain in the piezoelectric cantilever beam, so the pressure vs. voltage analysis is carried out to determine the relation between both parameters for better sensitivity which can be defined as voltage per applied pressure(MPa) which is shown in Fig 5.

To determine the capability of energy generation through the sensor, the pressure vs. charge density variation of the sensor is analyzed and is displayed in fig.6.

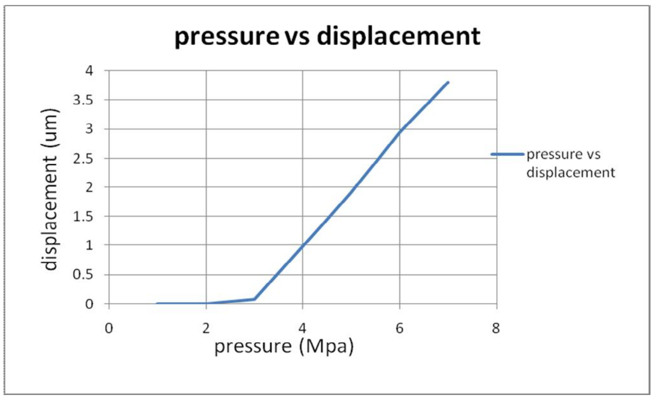

Fig .4: pressure vs. displacement of reference sensor dimention.

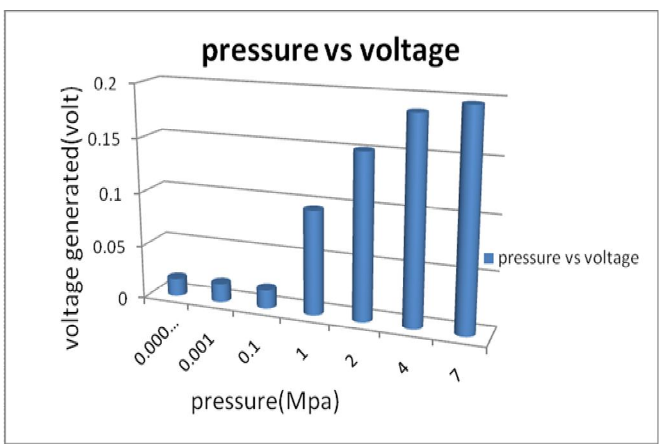

Fig .5: pressure vs. voltage of reference sensor dimensions

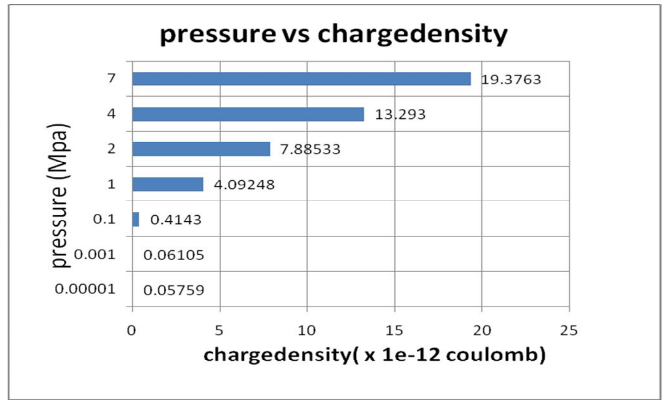

Fig. 6: pressure vs. charge density of reference sensor dimension.

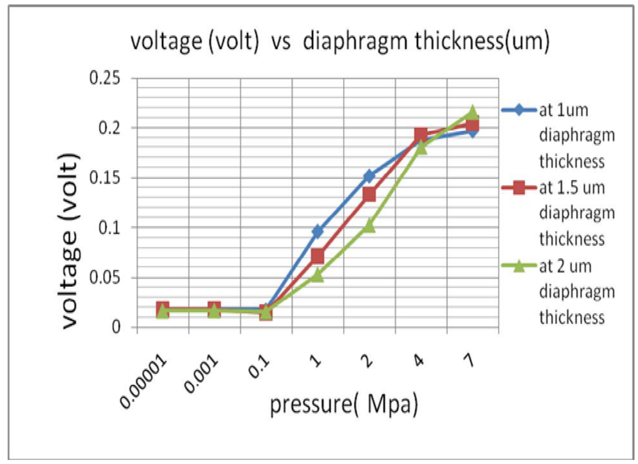

Fig. 7: variation of voltage vs. different diaphragm thickness

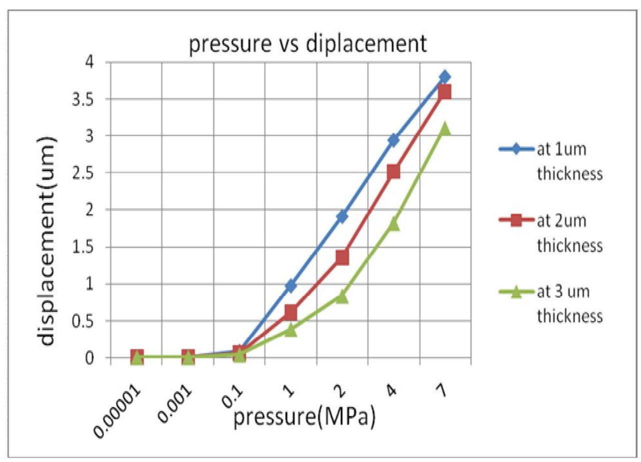

Fig. 8: variation of deflection vs. different diaphragm thickness.

It is observed that the charge density produced in the reference sensor on different applied pressure values, is directly proportional to each other.

Since the thickness of diaphragm and piezoelectric layer are equally responsible for energy generation and sensitivity measurement. Therefore by taking the piezoelectric layer thickness as constant and varying the thickness of the diaphragm as 1um, 1.5 um and 2 um respectively, all the related analysis are carried out to characterize the sensor structure as shown in fig 7, 8.

It is observed that the voltage is increasing with respect to the thickness variation of the sensor diaphragm.With decrease in thickness of the diaphragm, slope of the voltage vs applied pressure curve is more. At the same boundary conditions, with decrease in the diaphragm thickness, the pressure-deflection relationship is more as well as in linear region.

Now taking the diaphragm thickness as 1um and changing the thickness of piezoelectric layer from 1 um to 4 um with step size as 1um. After pressure-deflection analysis, it is found that the deflection is directly proportional to the pressure applied but within the refernce pressure range, its deflection is decreasing as the thickness is increased shown in fig 9, 10, 11.

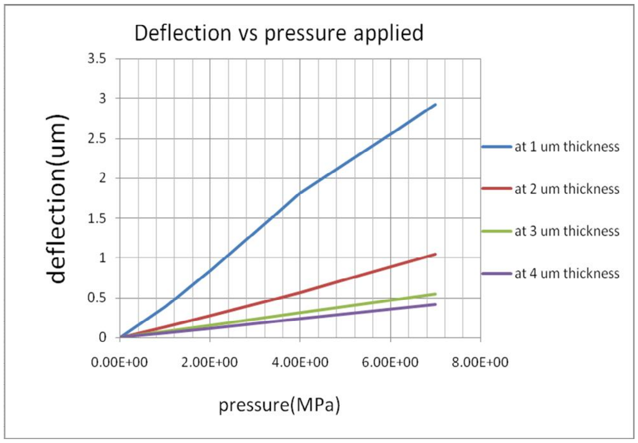

Fig. 9: variation of deflection vs. different piezoelectric layer thickness.

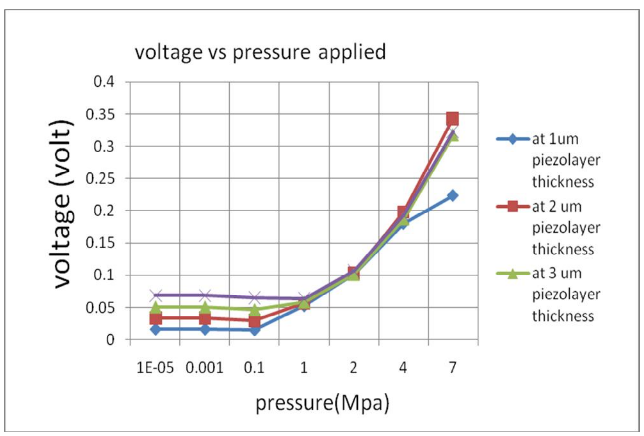

Fig. 10: variation of voltage generated vs piezoelectric layer thickness

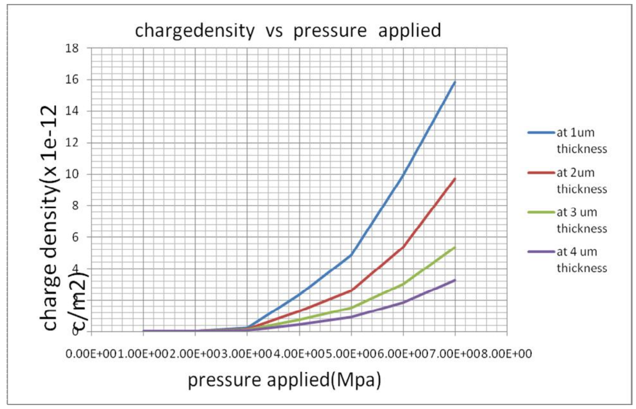

Fig .11: variation of charge density vs piezoelectric layer thickness

From the above analysis with respect to the thickness variation of the piezoelectric layer, it is observed that the charge density produced in the piezolayer is more in 1um thickness layer within the reference pressure range.

VI. CONCLUSIONS

The squared shaped piezoelectric self powered sensor is analyzed and the relationship between pressure-displacement, voltage-pressure as well as the pressure- charge density is derived. It shows that sensitivity of the sensor follows linear relationship and the voltage generated is dependent on the thickness of both the diaphragm and piezoelectric layer at the same conditions. Therefore to have the better sensitivity and energy conversion, optimization of both the layer is crucial one for self powered sensor designing. Also it is observed that lower thickness of diaphragm and piezoelectric layer is preferable to achieve larger voltage and better sensitivity. Therefore the same piece of material can be used for dual purposes and hence will reduce investments.With change in the materials and dimensions of the sensor, it can be used to further enhance the required goals.

VII. ACKNOWLEDGEMENT

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