A Novel Design and Modeling of Beam Bridge structure Piezoelectric Pressure Sensor base on ZnO

Maibam Sanju Meetei[a], Aheibam Dinamani Singh[b], Swanirbhar Majumder[b]

[a]*Department of Electronics and Communication, Rajiv Gandhi University, Doimukh, India*
[b]*Department of Electronics and Communication, North Eastern Regional Institute of Technology, Nirjuli, India*

Abstract:
The main objective of this study is to design a ZnO base beam bridge MEMS piezoelectric pressure sensor. A theoretical mathematical modeling of the design is derived for the structure. Factor effecting the output or efficiency is studied base on mechanical and electrostatics step by steps. A simulation is conducted on Comsol Multiphysics Simulator for the design for validating the theoretical modeling and a comparative study are made between the analytical and simulated result. This study will help to find the optimum design structure for piezoelectric pressure sensor base on bridge beam structure.

Keywords—Young modulus, Poisson Ratio, deflection,stress, voltage constant

1. Introduction

There are four common principle use for pressure to energy conversion – capacitive, inductive, piezoresistive [1-6] and piezoelectric [7–11]. Among these sensor, piezoelectric base MEMS sensor is a passive sensor as it doesn't require any electrical power excitation. Capacitive, inductive and piezoresistive MEMS sensor are active sensors as they required external power excitation.

Mechanical beam bridge structure is choosing for the study as it provides more stable then the cantilever type. In cantilever the structure is clamped or supported at one end whereas bridge beam structure is provides clamped or support at opposite two ends. In mechanical bridge beam structure or cantilever structure the maximum stress is occur at the edges of clamped area. The stress is directly proportional to charge developed on the surface of piezoelectric material. So in thisbeam structures the sensing material can be put at both the opposite edge.

Zinc Oxide (ZnO) is used for this study as it is widely available, low cost and most common material used in the research and industrial. ZnO has also wide application in the field of semiconductor and photo conductivity. It also has a high voltage constant. It hasthermochromicsproperties i.e. change in colour when heated from white to yellow, and when cooled down the colour back again to white colour because of various types of crystal lattice defects [12].

2. Illustrations

2.1. Mechanical Modeling

In this modeling, the applied pressure are converted into mechanical properties like deflection and stress. The basic theoretical differential equation of the beam was introducedin [13][14]. Let us consider for the coordinate system for a bridge beam structure as in Fig. 1.

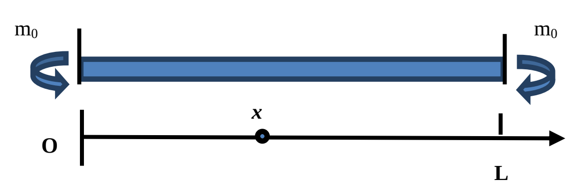

Figure 1: Structure of Bridge.

The governing mathematical expression of the equation is

$$-EIw''(x) = Fx/2 - Fx^2/2L - m_0, \quad (1)$$

where,E is Young's Modulus of the beam material, I is the moment of inertia of the structure, $w''(x)$ is the second derivative of the deflection for the beam at position x, F is the uniform force applied on the surface,x is the position on the beam, L is the length of the beam and m_0 is the moment on the clamped.

Equation (1) is integrated with respect to x and can be written as follow

$$-EIw'(x) = Fx^2/4 - Fx^3/6L - m_0x. \quad (2)$$

Putting the boundary on $w'(L) = 0$, the value of

$$m_0 = FL/12. \quad (3)$$

Equation (2) is integrated with respect to x and after putting the value of

m_0. The equation can be written as follow

$$-EIw(x) = Fx^3/12 - Fx^4/24L - FLx^2/24, \quad (4)$$

Or

$$w(x) = Fx^2(L-x)^2/(24ELI). \quad (5)$$

Equation (5) gives the deflection $w(x)$ of the beam at position x. The maximum deflection is occur at the centre of the beam i.e. $x = (L/2)$ so, the maximum deflection equation is given as follow

$$W_{max} = FL^3/(384EI). \quad (6)$$

The moment of inertia for the rectangular beam type given by the following equation

$$I = bh^3/12 \quad (7)$$

Equation (6) can be written after putting the value of I as follow

$$W_{max} = FL^3/(32Ebh^3). \quad (8)$$

The stress on the beam is given by the following expression

$$T(x) = -Ezw''(x). \quad (9)$$

Where, z is the distance from natural plain i.e. $z_0$of the beam. Natural plain is the plain where minimum stress has been occur in the geometry,when pressure is applied on the structure. Generally, it is the mid plain of the beam for single layer.

Equation (1) can be written after putting the value of m_0 and I on (9),

$$T(x) = zF(6x^2 - 6xL + L^2)/ bh^3L. \quad (10)$$

For single layer the maximum stress is occur at $x = L$ and $x = 0$ on the top of the surface i.e. for single layer $z = h/2$. Equation (10) can be rewritten as follow

$$T_{max} = FL/2bh^2. \quad (11)$$

For multiple layers geometry have different layers like silicon layer, silicon dioxide, metal electrode and sensing layer etc. In such case the value of z is depend on the natural plain i.e. z_0.

Consider a multi-layer composite system as in fig. 2. In [13], the natural plain position can be determine by the following equation

$$z_0 = (E_1\, t_1\, (z_1+0)+E_2\, t_2\, (z_2+z_1)+\ldots+E_n\, t_n(z_n+z_{(n-1)}\,))/(2(E_1\, t_1+E_2\, t_2+\ldots+E_n\, t_n) \quad (12)$$

Where, $E_1, E_2 \ldots E_n$ are the Young's modulus of the layers for the layers with $t_1, t_2\ldots t_n$ are the thickness of the layers respectively. And the value of $z_n$is given by the following formula

$$z_n = \sum_{j=1}^{n} t_j, \quad (13)$$

where, $i = 1, 2, 3, 4, \ldots n$.

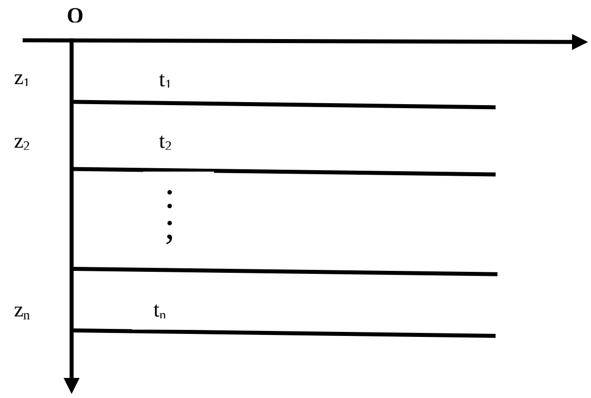

Figure 2:multi-layer composite system.

2.2 Electroststic Modeling

In [15], the conversion of mechanical stress to electrostatic charge for ZnO piezoelectric is given by the following expression

$$q(x) = T(x)d_{31}, \quad (14)$$

where, d_{31} is the strain constant of ZnO, q(x) is the total charge developed on the surface.
For the conversion of mechanical stress to electrostatic voltage is given by the following expression

$$V(x) = T(x)tg_{31}, \quad (15)$$

where, g_{31} is the voltage constant of ZnO, V(x) is the voltage developed between the surfaces and t is the thickness of the piezoelectric.

3. Design model and simulation

A model has been design for prediction in the Comsol Multi-Physics Simulator. In simulation, the physics used is Electromechanical and the study is Stationary. Here, a bridge consisting of Silicon (Si) layer as mechanical structure, Silicon-dioxide (SiO_2) layers as insulator between Si and electrodes, Gold (Au) as electrodes and ZnO layer piezoelectric is consider as shown infig. 3. The dimensions of the each layers are tabulated in table no. 1

Table 1: Dimension and Properties used in design.

Parameters	Symbols	Value	Unit
Dimension of Si	$(L \times B \times T)_1$	300x50x10	µm³
Dimension of SiO_2	$(L \times B \times T)_2$	300x50x3	µm³
Parameters	Symbols	Value	Unit
Dimension of Au	$(L \times B \times T)_3$	50x50x1	µm³

Dimension of ZnO	**(L x B x T)₄**	**50x50x5**	**µm³**
Young's Modulus of Si	**E_1**	**160**	**GPa**
Young's Modulus of SiO_2	**E_2**	**70**	**GPa**
Young's Modulus of Au	**E_3**	**70**	**GPa**
Young's Modulus of ZnO	**E_4**	**120**	**GPa**
Strain Constant of ZnO	**d_{31}**	**-5.43 X 10^{-12}**	**m/V**
Voltage Constant of ZnO	**g_{31}**	**-4.85 X 10^{-2}**	**Vm/N**
Applied Pressure	**p0**	**200**	**Pa**

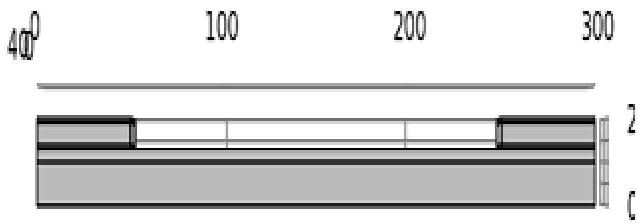

Figure 3:Design Structure

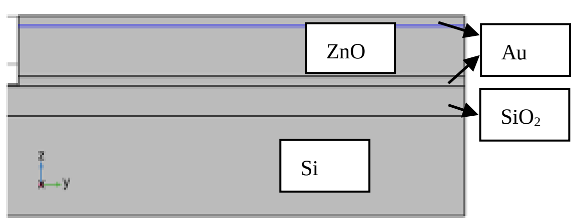

Figure 4:Multilayer in sensing area

4. Simulation Output

4.1 Deflection and Stress

In mechanical design, the deflection and the stress is an important parameters for study. As the maximum deflection is occurs at mid of the bridge but the maximum stress is occur at the edges on the ends of the bridge. As from the deflection output as shown in fig. 5 the maximum deflection is occur at the centre of the bridge.

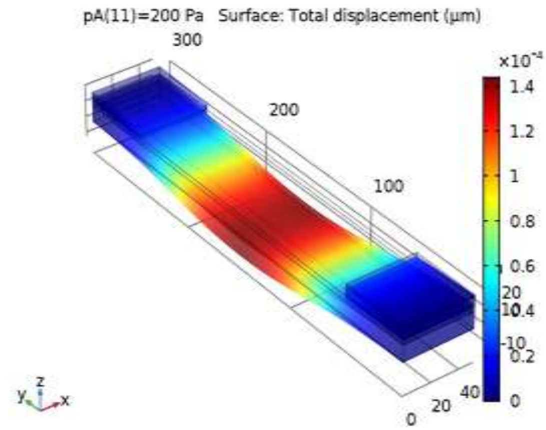

Figure 5: Simulation output showing maximum deflection at the center.

The analytical deflection value and simulated deflection value with different applied pressure is tabulated as in table 2.

Table 2: Pressure Vs Maximum deflection for analytical and simulated.

Sl. No.	**Pressure Vs Maximum Deflection**		
	Applied Pressure [Pa]	***Analytical [µm]***	***Simulated [µm]***
1	0	0	0
2	20	1.440E-5	1.436E-5
3	40	2.880E-5	2.871E-5
4	60	4.320E-5	4.303E-5
6	80	5.760E-5	5.732E-5
7	100	7.200E-5	7.147E-5
8	120	8.641E-5	8.623E-5
9	140	10.081E-5	10.001E-5
10	160	11.521E-5	11.483E-5
11	180	12.962E-5	12.901E-5
12	200	14.402E-5	14.362E-5

But for the stress, the maximum stress is occur at the edges of the joint as shown in fig. 6.

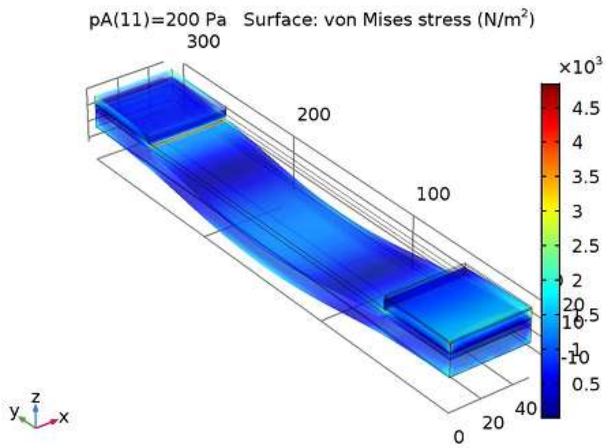

Figure 6: simulation output showing maximum stress at the edges.

The analytical maximum stress value and simulated stress value are tabulated as in table 3.

Table 3: Pressure vs Maximum Stress for analytical and simulated.

Sl. No.	Pressure Vs Maximum Stress		
	Applied Pressure [Pa]	*Analytical [N/m²]*	*Simulated [N/m²]*
1	0	0	0
2	20	2250	2363
3	40	4500	4778
4	60	6750	7162
6	80	9000	9813
7	100	11250	12099
8	120	13500	14767
9	140	15750	16720
10	160	18000	19593
11	180	20250	21744
12	200	22500	24662

In electrostatic design, the potential difference across the upper layer and lower layer of the piezoelectric material is studied. The potential voltage is developed due to the charge is developed due to the stress induced on the sensing material. The developed surface voltage is directly proportional to the pressured or force applied on the material. The simulation output is showing the potential developed at applied pressure as in fig.7.

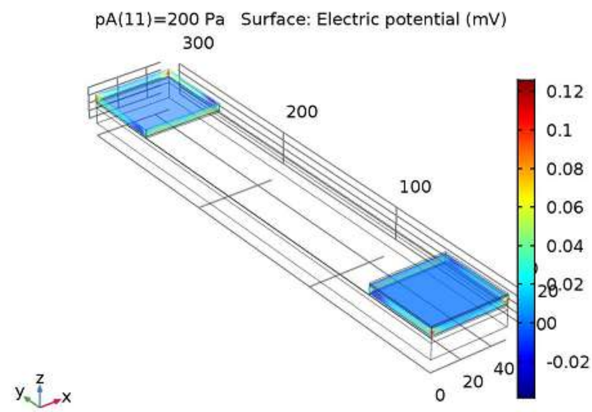

Figure 7: Simulation output is showing the potential developed.

The analytical potential difference value and simulated potential difference value are tabulated as in table 4.

Table 4: Pressure Vs Potential Differences.

Sl. No.	Pressure Vs Potential Differences		
	Applied Pressure [Pa]	*Analytical [mV]*	*Simulated [mV]*
1	0	0	0
2	20	0.0909	.09107
3	40	0.1819	0.2298
4	60	0.2728	0.3271
6	80	0.3637	0.3943
7	100	0.4547	0.4928
8	120	0.5456	0.59145
9	140	0.6366	0.6900
10	160	0.7275	0.7886
11	180	0.8184	0.8871
12	200	0.9094	0.9785

5. Discussion and Conclusions

A theoretical modeling approach for design piezoelectric beam bridge pressure sensorhas established and validate by using Comsol Multiphysics simulator. As the simulated output and analytical output of *the very close, this design process can be implemented for designing the ZnO piezoelectric beam bridge pressure. This design process can be implemented for optimizing of the sensor too. The various factor affecting the sensitivity are applied pressure, dimension of the sensor structure, Young'smodulus (E), Poison's ratio (v) and the voltage constant (g_{31}). The sensitivity is also affected by the material used in the multilayer structure since the Young's modulus and Poison's ration has different value for different material. The ZnO is used because it has high voltage constant. The mechanical sensitivity of the deflection to applied pressure and stress to applied pressure are 0.071µm/Pa and 118 N/m^2Pa respectively. The electrostatic sensitivity or the overall sensitivity of the sensor is 0.00489 mV/Pa. This designed sensor can be implemented for low pressure sensor as the sensitivity is very high.*

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