DESIGN AND SIMULATION OF FORCE SENSOR WITH PIEZO RESISTIVE RECTANGULAR STRAIN GAUGE

(Date received: 22.11.2007)

Thangamani U, Mohd. Yunus Hamid and Ali Chekima
Centre for Artificial Intelligence, School of Engineering and Information Technology,
Universiti Malaysia Sabah, Sabah
Email: uthangamani@yahoo.co.in

ABSTRACT

The design and simulation of force sensor with piezo resistive rectangular strain gauge is presented in the paper. A piezo resistive metal gauge on thin rectangular membrane is designed based on ANSYS simulation result. A force sensor having piezo resistive rectangular strain gauge on thin plate is designed. The simulation result yields the percentage of strain transferred from thin plate to substrate and to the gauge due to the applied force. Theoretical studies on piezo resistive metallic gauge on rectangular membrane and force sensor are presented. A maximum of 0.70348με and maximum resistance change in gauge (grid) = 177.27μΩ are achieved for an applied force of 1mN.

Keywords: *Finite Element Analysis, Metal Gauge, Piezo Resistive, Rectangular Membrane, Strain Gauge*

1. INTRODUCTION

A strain gauge converts force, pressure, tension, weight in to a change in electrical resistance which can then be measured. The operational principle of metal gauge is based on the fact that any electrical conductor changes its resistance with mechanical stress. It is due to changes in the conductor cross section and resistivity caused by micro structural changes. The size of the strain gauge is usually decided by the space available or by the topography of the strain field. There is no physical constraint in choosing the gauge dimension [1]. Strain gauge equations are derived based on small deflection theory [2 - 4]. Finite element tool, ANSYS, is used to find the maximum strain distribution location on the membrane. It allows choosing the desired gauge orientation and active region on the membrane to achieve maximum sensitivity. Materials like Polyimide, Polystrene, and Silicon are studied as a substrate for gauge design. However, Polyimide is found to develop maximum strain (Figure 1) and hence it is chosen as a substrate for gauge design [5, 6]. With its ease of handling and its suitability for use over the temperature range from -195˚C to +175˚C, Polyimide is an ideal substrate for general purpose static and dynamic stress analysis. The alloy 'constantan' is used as gauge (grid) material for strain gauge design. It is a commonly used as a peizoresistive metal gauge material. Its high peel strength makes the gauge less sensitive to mechanical damage during installation [7]. To the knowledge of authors, there has been no theoretical study exists on piezo resistive metallic gauge on rectangular membrane for strain measurement. In the present study, equations are derived for piezo resistive metallic gauge on the rectangular membrane for strain measurement. A force sensor is designed using this strain gauge and its individual components strain distribution is analysed. In addition, the percentage of strain transformed from one component to another component is calculated. This feature could be used to choose the right material for the design effectively.

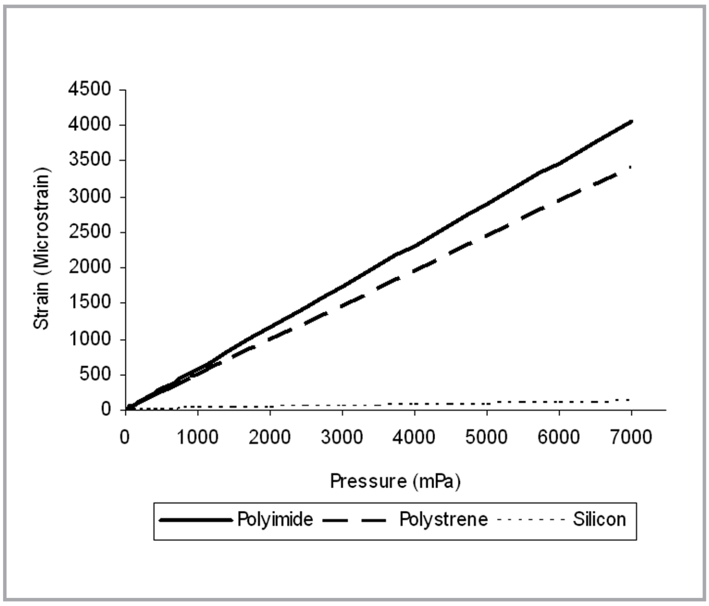

Figure 1: Different substrate materials

2. THEORETICAL STUDY

The change in resistance of the gauge on the rectangular membrane due to an applied load is calculated by strain developed in the membrane and passed on to the gauge. It is discussed in the following subsections [8].

2.1 STRAIN ON RECTANGULAR MEMBRANE

The strain distribution on a rectangular membrane depends on its geometry, boundary conditions and applied load. There are two different cases discussed in this paper. They are the supported edges and the clamped edges. The applied pressure P is constant over the entire membrane.

2.2.1 Supported edge: The maximum strain developed at the long side edges as shown in Figure 2 is due to applied pressure P. The strain on the membrane is given by Equation (1) [9].

$$\varepsilon_{max} = \frac{\beta P w^2}{Y t^2} \qquad (1)$$

where β is a constant, which varies with respect to aspect ratio. *w* is the width of the membrane. *P* is the applied pressure, *t* is the thickness of the membrane, and *Y* is the Young's modulus of the membrane material.

2.1.2 Clamped Edge: The maximum strain developed at center of the membrane as shown in Figure 3, is due to the applied pressure P. The strain on the membrane is given by Equation (2) [9].

$$\varepsilon_{max} = \frac{\beta_1 P w^2}{Y t^2} \qquad (2)$$

where β_1 is a constant, which varies with respect to aspect ratio. *w* is the width of the membrane. *P* is the applied pressure, *t* is the thickness of the membrane, and *Y* is the Young's modulus of the membrane material.

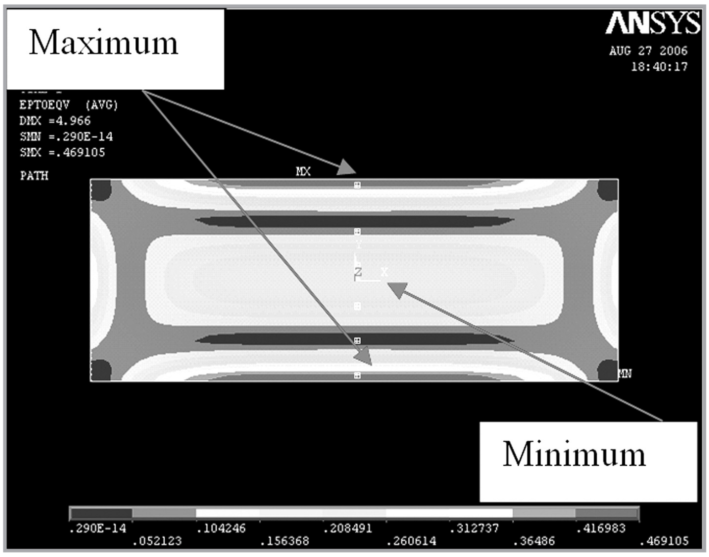

Figure 2: Supported edge

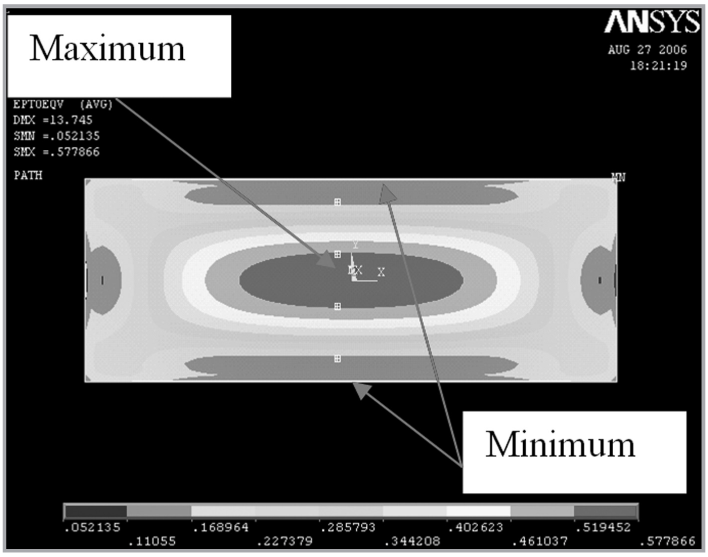

Figure 3: Clamped edge

2.2 STRAIN ON GAUGE

The resistance of the gauge (grid) is given by Equation (3) [10].

$$R = \rho \frac{\iota}{A} \qquad (3)$$

$$A = WT \qquad (3)$$

where, *A* is area of the gauge (grid) wire,
where, *l* is the length of the gauge wire, *W* is the width of the gauge wire, *T* is the thickness of the gauge wire, and ρ is the resistivity of the gauge wire. Under strain the rate of changes in *R*.

$$\frac{dR}{R} = \frac{dl}{l} - \frac{dA}{A} + \frac{d\rho}{\rho} \qquad (5)$$

$$\frac{dA}{A} = \frac{dW}{W} + \frac{dT}{T} \qquad (6)$$

where *dW* and *dT* written in terms of strain are given by Equations (7) and (8) [11].

$$dW = -\gamma \varepsilon W \qquad (7)$$

$$dT = -\gamma \varepsilon T \qquad (8)$$

$\frac{dR}{R}$ Can thus be rewritten as

$$\frac{dR}{R} = (1 + 2\gamma)\varepsilon + \frac{d\rho}{\rho} \qquad (9)$$

where γ is the Poisson's ratio and ε is the strain.

The fractional change in resistivity, $\frac{d\rho}{\rho}$, is due to piezo resistivity[11].

In metals, $\frac{d\rho}{\rho}$ is related to fractional change in volume, $\frac{dV}{V}$ [6].

$$\frac{d\rho}{\rho} = \mathrm{K}\frac{dV}{V} = \mathrm{K}\left(\frac{dl}{l} + \frac{dA}{A}\right) \qquad (10)$$

as $V = lA$

$$\frac{d\rho}{\rho} = K\varepsilon(1 - 2\gamma) \qquad (11)$$

where *K* is the Bridgman constant, $1.13 \le K \le 1.15$
Substituting Equations (11) in to (9) yields

$$\frac{dR}{R} = \varepsilon[1 + \mathrm{K} + 2\gamma(1 - K)] \qquad (12)$$

Equation (12) is used to calculate the changes in the gauge resistance due to strain, ε, developed on membrane.

2.3 RESISTANCE CHANGE IN THE GAUGE IN TERMS OF STRAIN DEVELOPED ON MEMBRANE

For the supported edge case, the changes in the gauge resistance are obtained by Equations (12) and (1).

$$dR = R\left[\frac{\beta P w^2}{Y t^2}\right][1 + K + 2\gamma(1 - K)] \qquad (13)$$

For the clamped edge case, the changes in the gauge resistance are obtained by Equations (2) and (12).

$$dR = R\left[\frac{\beta_1 P w^2}{Y t^2}\right][1 + K + 2\gamma(1 - K)] \qquad (14)$$

2.4 FORCE SENSOR

The piezoresistive strain gauge designed by ANSYS simulation result is used to design the force sensor. To design the force sensor the strain gauge is fixed on one end of thin plate, P′, as shown in Figure 4. The other end of thin plate is free which is used to apply a load. Since the strain gauge (clamped) fixed on the thin plate, clamped edge boundary condition strain gauge Equation (14) used to develop the force sensor. Therefore the force sensor equation is given by Equation (15).

$$dR = R \text{ x } [1 + K + 2\gamma(1 - K)] \text{ x } \varepsilon_s \qquad (15)$$

Where, ε_s is the function of strain in substrate due to strain transferred from the thin plate.

Strain in substrate is, $\varepsilon_s = \dfrac{\beta_2 \varepsilon_{P'} w^2}{Y t^2}$

where, $\varepsilon_{p'}$, is the strain in thin plate, $\varepsilon_{p'} = \dfrac{6F(L - x)}{Y_1 w_1 t_1^2}$

where F is the applied force, L is the total length of the thin plate, $(L - x)$ is the gauge distance from the applied force, F, Y_1 is the Young's modulus of the thin plate, P′, w_1 is the width of the thin plate, and t_1 is the thickness of the thin plate as shown in Figure 4.

3. SIMULATION

The finite element analysis software ANSYS [12–14] is used to find the strain distribution and the strain calculation on the sensor components. The strain distribution is used to choose the maximum strained area on the substrate for gauge design. This allows to design highly sensitive strain gauges. However, the strain calculation on sensor components are used to calculate percentage of strain transferred from one component to another component. This helps to find out maximum strained components and these values are given in Tables 2 and 3. The design tool Pro ENGINEER is used to design the sensor components such as thin plate, P′, substrate, and the gauge. ANSYS solid brick element having 8 node 185 structure is used for finite element analysis since it is generally used for bending strain and stress analysis.

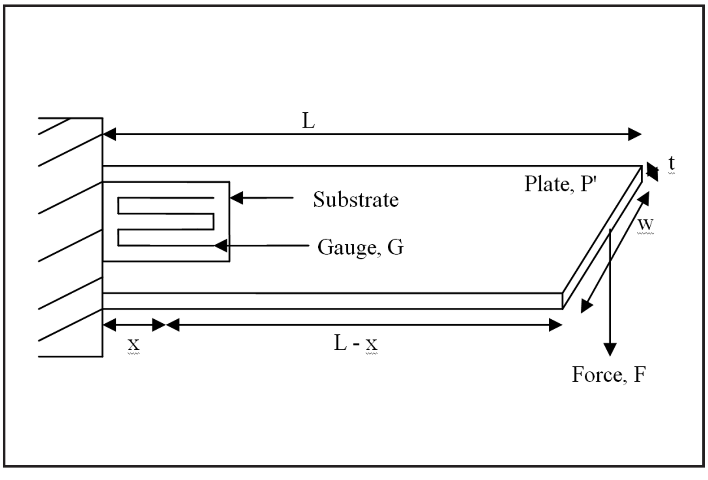

Figure 4: Force sensor

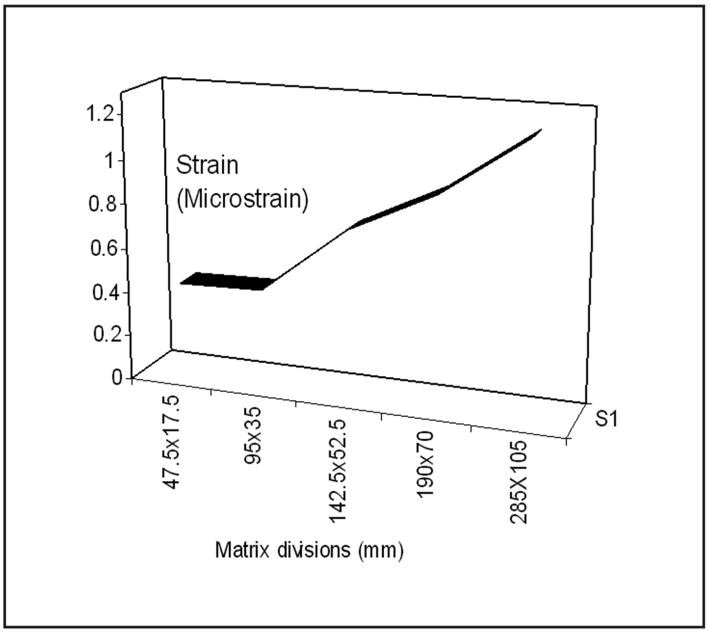

Figure 5: Strain variation vs Matrix divisions

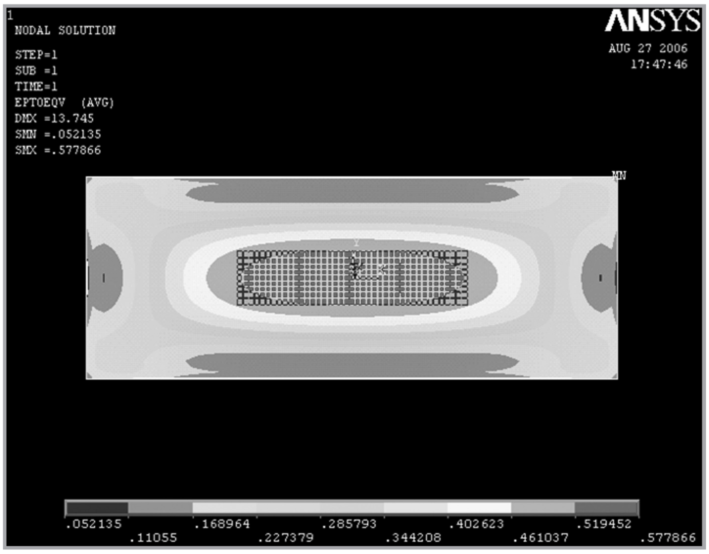

Figure 6: Maximum strained area represented by rectangle box

3.1 SUBSTRATE AND GRID

A substrate having a length 9.5 mm, a width 3.5 mm, and a thickness = 0.05 mm is chosen in this paper for the design and analysis. The substrate is simulated for the supported and clamped edge boundary conditions. The maximum and minimum strained locations of both the clamped and supported edge substrates are marked as shown in Figures 2 and 3 respectively. In Figure 2, the maximum strain locations for supported edges are at the long side edges. Since the minimum strained locations are at the center, the gauge design on the center area is insensitive. Hence, the clamped edge boundary condition is used for the strain gauge design. The substrate mesh element matrix size is 95 x 35 divisions since its dimension 9.5cm x 3.5 cm. Because of limitation at convergence, the mesh element matrix size should not exceed 95, 35. Successive iteration result shown in Figure 5

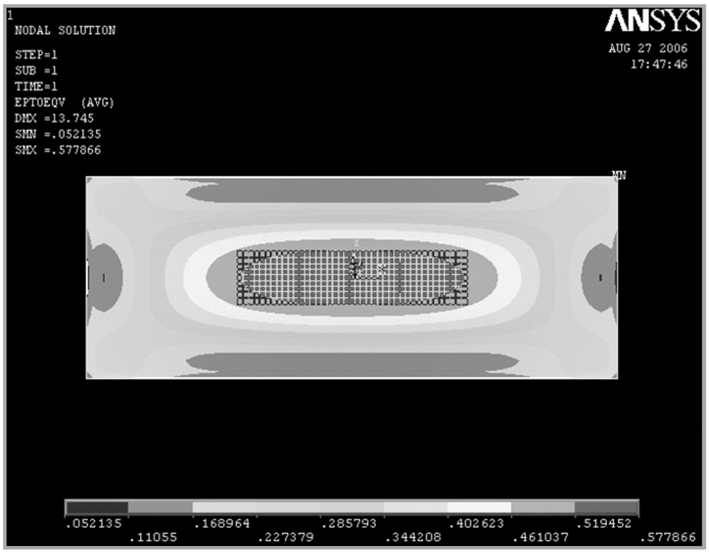

Figure 7: X–Component strain distribution

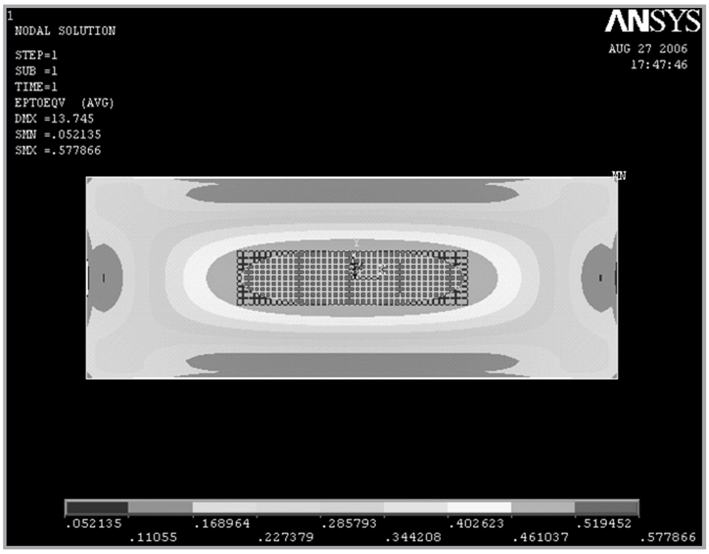

Figure 8: Y–Component strain distribution

Figure 9: Gauge pattern on maximum strained area of substrate

should be less than 5% to get maximum strain location at center as shown in Figure 6. However, the increase of matrix division increases strain (Figure 5) but the maximum strain distribution area is shifted towards long side edges as in Figure 2. For smaller value of the matrix dimensions, the maximum strain distribution area remains at the center but its strain value decreases. Therefore, the maximum strain value and its corresponding strain area are based on the convergence limitations. The area of maximum strained region i.e., active region for gauge design is found to be 3.9mm x 0.9mm as shown in Figure 6. A 7 loop strain gauge is designed in this paper since the same number of loop gauges is used in the industry. An active length = 3.9mm, a single line width = 0.0333mm, and a thickness = 0.003mm gauge (grid) pattern is designed and assembled on the maximum strained area found (Figure 6) as shown in Figure 9. The substrate and the gauge are meshed independently while maintaining the continuity.

The strain variation with matrix divisions is shown in Figure 5. Though the strain value increases with increase of matrix division, its convergence limits the mesh element size, i.e., the successive iteration of element size result must be less than 5%. Increasing the value of matrix division shifting the maximum strained area to the long side edges as in Figure 2.

The maximum strain developed area is represented by rectangular box as shown in Figure 6. Design of gauge (grid) pattern on this Red region allows us to get maximum sensitivity. The gauge pattern also designed and analysed for other contours such as Brown, Yellow, Yellow2, and Green. The results are given in Table 1.

The strain distribution in X-component is given in the Figure 7. Since the maximum strain (shown in Red colour) concentrates at the center area and the areas near the middle edge of the membrane, the piezo resistive gauge should be arranged within this area [15].

Table 1: Area of different contours and its corresponding strain

Colour	Length (mm)	Width (mm)	Strain in Gauge (με)	Strain in Substrate (με)	Strain in Substrate and Gauge (με)	% Strain transferred from substrate to gauge (με)
Red	3.9	0.9	0.3241	0.4052	0.4403	79.9851
Brown	5.2	1.3	0.2382	0.3470	0.3924	68.6455
Yellow	6	1.7	0.0998	0.1874	0.2728	53.2550
Yellow2	6.7	1.9	0.0982	0.1459	0.2341	61.1377
Green	7.3	2.1	0.0688	0.1372	0.2184	50.1457

Table 2: Strain in gauge, substrate, and the combination of gauge and substrate

Pressure	Strain in gaue (με)	Strain in substrate (με)	Strain in gauge and substrate (με)	% Strain transferred from substrate to gauge
1	0.3246	0.40527	0.44039	80.0947
10	3.242	4.053	4.404	79.9901
20	6.483	8.106	8.808	79.9777
40	12.966	16.211	17.616	79.9827
60	19.45	24.317	26.424	79.9851
80	25.933	32.422	35.232	79.9858
100	32.416	40.528	44.04	79.9842
200	64.832	81.055	88.079	79.9851
300	97.248	121.583	132.119	79.9848
400	129.66	162.111	176.159	79.9847
500	162.08	202.638	220.199	79.9854
600	194.49	243.166	264.238	79.9852
700	226.91	283.964	308.278	79.9090
800	259.32	324.221	352.318	79.9852
900	291.74	364.749	396.357	79.9851
1000	324.16	405.277	440.397	79.9850

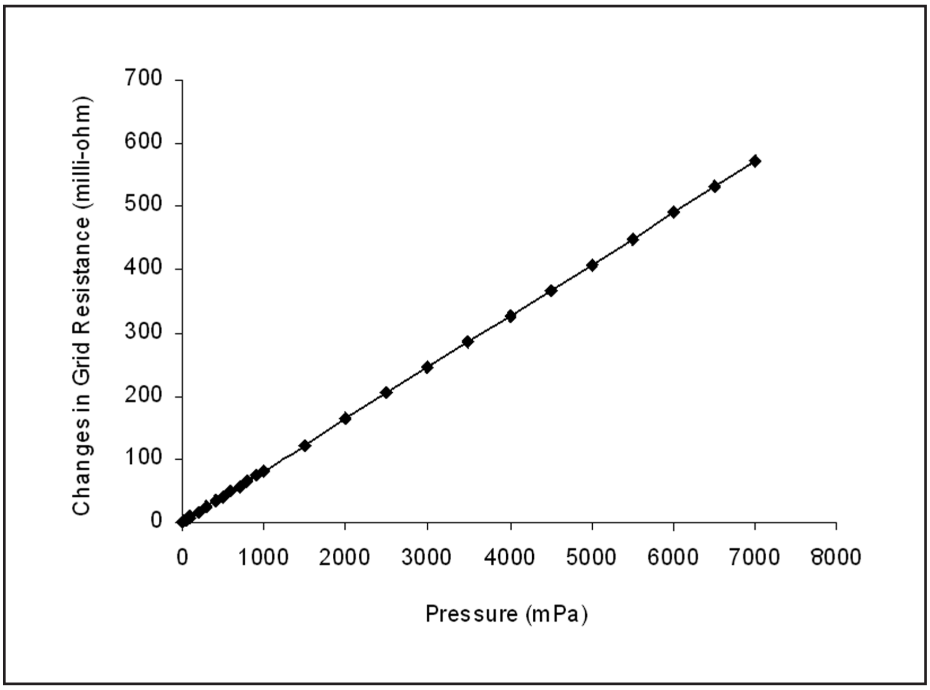

Figure 10: Resistance change in gauge variation vs applied load

The maximum strained area on substrate can be determined from Table 1. Furthermore, the strains on gauge and the substrate are calculated independently. However, the percentage of strain transformed from substrate to gauge is calculated and given in Table 1. The red colour contour and its corresponding gauge (grid) pattern design provides maximum strain. It also provides maximum percentage of strain transferred from substrate to grid through red contour. Hence the red contour is chosen for the gauge design.

For different values of pressure, strain gauge and its components strain values are given in Table 2. Percentage of strain transformed from the substrate to the grid is constant for all pressure. This shows that the gauge (grid) pattern is designed exactly on the maximum strained area of the substrate. This helps to achieve maximum sensitivity.

The linear variation of resistance change with respect to applied pressure on the substrate is shown in Figure 10. This reveals that the gauge resistance has linear response to the applied pressure. The maximum applied pressure and its corresponding strain obtained for Polyimide substrate is 70Pa and 4051με respectively. Similarly, for Polystrene, 85Pa is the maximum applied load and its maximum strain is 41540με and for silicon 2.5KPa is the maximum applied load and its maximum strain is 41204με. All of the three substrate materials behave non-linearly when the applied pressures are larger than the above values. These results are obtained by ANSYS simulation.

3.2 FORCE SENSOR

A force sensor is designed and analyzed by Pro ENGINEER and ANSYS [15] respectively. It includes a thin plate, P′, a substrate, and a gauge. A thin plate, P′, having a length of 20mm, a width of 7mm, and a thickness of 0.1mm is chosen in this paper. The strain distribution on thin plate is shown in Figure 11. It is used to find out maximum strained locations on beam to fix strain gauge on it. From Figure 11, the maximum strain distribution is only at the fixed edge. Whereas, the minimum strains developed on free edge. Hence, the strain gauge is fixed at maximum strain area to achieve maximum sensitivity.

The strain distribution on sensor components such as the thin plate, P′, the substrate, and the gauge is shown in Figure 12. The strain developed on the force sensor and its components are given in Table 3. It is used to calculate percentage of strain transformation from one component to another component such as thin plate, substrate, and gauge (grid) and helps to study material performance under different load. However, this analysis allows choosing right material, dimension, and orientation of components before fabrication.

CONCLUSION

Design and simulation of a piezo resistive metal gauge and a force sensor have been studied. Equations were obtained for the metal gauge on rectangular membrane and force sensor. Different

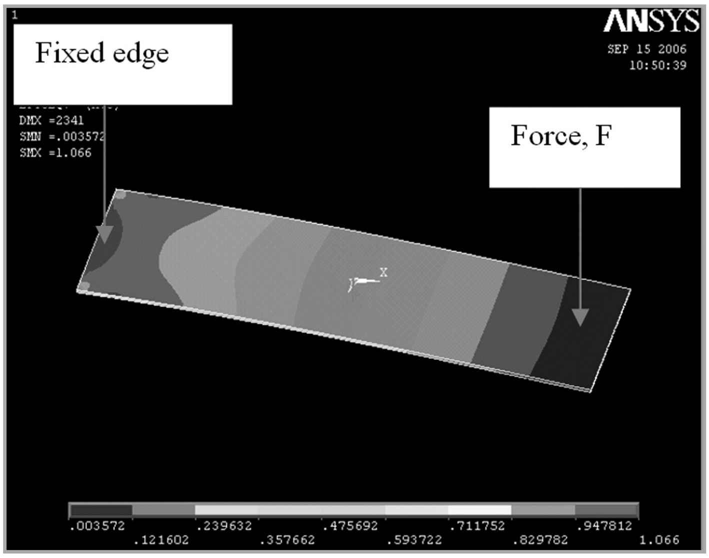

Figure 11: Strain distribution on thin plate, P'

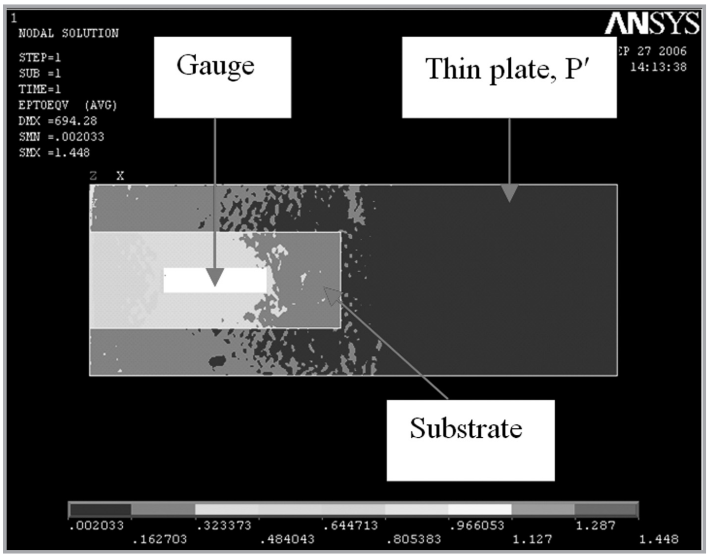

Figure 12: Strain distribution in thin plate, substrate, and grid

Table 3: Force sensor results

Pressure	Strain in Gaue (με)	Strain in Substrate (με)	Strain in Beam (με)	Strain in all the three Material (με)	% Strain transferred from Substrate to Gauge	% Strain transferred from Beam to Substrate
1	0.70348	1.195	0.4856	1.448	58.86861925	246.0873147
10	7.035	11.949	4.857	14.481	58.87521968	246.0160593
20	14.07	23.899	9.714	28.961	58.87275618	246.0263537
30	21.104	35.484	14.571	43.442	58.87078777	246.0229222
40	28.139	47.797	19.427	57.923	58.87189573	246.0338704
50	35.174	59.747	24.284	72.403	58.87218255	246.0313647
60	42.209	71.696	29.141	86.884	58.87157514	246.034426
70	49.244	83.464	33.998	101.364	58.87191258	246.0321195
80	56.278	95.595	38.855	115.845	58.87127988	246.030112
90	63.313	107.544	43.712	130.326	58.87171762	246.0285505
100	70.348	119.494	48.569	144.806	58.87157514	246.0293603
200	140.696	238.987	97.137	289.613	58.87182148	246.0308636

substrate materials were studied and Polyimide was chosen as a substrate for the strain gauge design. The maximum strained locations were identified on the substrate for different boundary conditions. The gauge patterns were designed for different contours. The maximum strained area and its corresponding gauge pattern was chosen as a strain gauge. A force sensor was designed by the designed piezo resistive metal strain gauge, and its simulation results show that the resistance change of gauge is linear to the applied force. The simulation result allows us to calculate percentage of strain transferred from thin plate to substrate and to the gauge and also has been used to calculate individual sensor components strain values. ■

REFERENCES

[1] Joyce. D, Scott. M. Force and Mass Determination by Strain Gauge. Significance of Calibration, IEE Colloquium on (IEEEXplore) (1993) pp. 301-310.

[2] William P. Eaton, Fernando Bitsie, James H. Smith and David W. Plummer. A New Analytical Solution for Diaphragm Deflection and its Application to a Surface-Micromachined Pressure Sensor. International Conference on Modeling and Simulation of Microsystems, MSM99 (1999).

[3] S.P. Timoshenko and S. Woinowsky-Krieger, Theory of Plates and Shells, 2nd ed. New York: McGraw-Hill, (1970).

[4] R. Szilard, Theory and Analysis of Plates: Classical and Numerical Methods. Englewood Cliffs, NJ: Prentice-Hall, (1974).

[5] Mohd Yunus Hamid, Thangamani U and Pukhraj Vaya. Simulation of Piezoresistive Metal Gauge on Rectangular Membrane for Low Pressure Applications. ICSE2006Proc. (2006) pp. 304 -308.

[6] Thangamani U, Mohd Yunus Hamid, Pukhraj Vaya, Siva Prasad. Simulation of Strain in Rectangular Membrane for Piezoresistive Sensor. Proceedings of International Conference on Man-Machine Systems (2006).

[7] A. L. Window. Strain Gauge Technology, 2nd ed. Elsevier applied science (1982).

[8] W. K. Schomburg, Z. Rummler, P. Shao, K. W. Wulff, and L. Xie. The Design of Metal Strain Gauge on Diaphragms. IOP Publishing J. Micromech Microeng. (2004). Vol. 14, pp. 1101-1108.

[9] Warren C. Young., Richard G. Budynas. Roark's Formulas for Stress and Strain, 7th ed. McGraw-Hill (2002).

[10] William M. Murray and Willim R. Miller. The Bonded Electrical Resistance Strain Gauge – An Introduction. Oxford University Press Inc. (1992).

[11] Chris Field and David M. Beams. Project Guise: Introduction to Strain Gauges, Dept. of Electrical Engineering, University of Texas, Tyler (2005).

[12] ANSYS, Finite Element Analysis Program, Swanson analysis systems, Inc, ANSYS Inc, Canonsbury, PA, (1996).

[13] Liwei Lin, Huey-Chi Chu, and Yen-Wen Lu. A Simulation Program for the Sensitivity and Linearity of Piezoresistive Pressure Sensors. Journal of Microelectromechanical Systems, (1999). Vol.8, No.4

[14] M. H. Orhan, C. Dogan, H. Kocabas, and G. Tepehan. Experimental Strain Analysis of the High Pressure Strain Gauge Pressure Transducer and Verification by using a Finite Element Method. Meas. Sci. Technol. 12 (2001) pp. 335-344.

[15] Li Cao, Tae Song Kim, Susan C. Mantell, and Dennis L. Polla. Simulation and Fabrication of Piezoresistive Membrane type MEMS Strain Sensors. Sensors and Actuators A: Physical, (2000). Vol. 80, No. 3, pp. 273 – 279.

PROFILES

MOHD. YUNUS BIN HAMID

Mohd. Yunus bin Hamid was born in Kota Kinabalu, Sabah, Malaysia. He received the BSc. in Electrical Engineering in 1998 from Wichita, USA and PhD. from UK in 2003. Since 2003 he is working as Lecturer at Universiti Malaysia Sabah (UMS). Since 2006 he is a Director for Centre for Artificial Intelligence at UMS. His research interests includes sensors technology, Intelligent Communication Systems, pre-equalisations (pre-rake), multiuser communications, spread spectrum, 3G/4G systems and implementation issues in CDMA mobile radio sytems.

THANGAMANI U.

Thangamani receieved the B.Sc. degree in Physics from Bharathidasan University, Tamilnadu, India in 1997 and the M.Sc., degree in Applied electronics from National Institute of Technology, Trichy (NITT), India in 2000. He has worked with GPS receiver simulator development team at Madras Institute of Technology (MIT), Anna University, Madras, India in 2001. He has received his embedded system engineer course from Accel Technology, Madras, India in 2003. He is currently working toward the PhD. degree in the area of Microelectronics at Universiti Malaysia Sabah, Sabah, Malaysia.

ASSOC. PROF. ALI CHEKIMA

Ali Chekima received his BEngg in Electronics from Ecole Nationale Polytechnique of Algiers in 1976 and his MSc and PhD both in Electrical Engineering from Rensselear Polytechnic Institute Troy, New York, in 1979 and 1984 respectively. He joined the Electronics Department at the Ecole Nationale Polytechnique in 1984, where he was chairman of the Scientific committee of the Department as well as in charge of the postgraduate program while teaching at both graduate and undergraduate levels.. He was member of several scientific committees at the national level. He has been working as an Associate Professor at the School of Engineering and Information Technology at Universiti Malaysia Sabah since October 1996. His research interests include Source Coding, Antennas, Signal Processing, Pattern Recognition, Medical Imaging, Data Compression, Artificial Intelligence and Data Mining. He has published more than 60 papers in refereed journals, conferences, book chapters and research reports.