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Design and analysis of MEMS MWCNT/epoxy strain sensor using COMSOL

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Abstract. The design and performance of piezoresistive MEMS-based MWCNT/epoxy composite strain sensor using COMSOL Multiphysics Toolbox has been investigated. The proposed sensor design comprises su-8 based U-shaped cantilever beam with MWCNT/epoxy composite film as an active sensing element. A point load in microscale has been applied at the tip of the cantilever beam to observe its deflection in the proposed design. Analytical simulations have been performed to optimize various design parameters of the proposed sensor, which will be helpful at the time of fabrication.

Keywords. COMSOL; MWCNT; epoxy; piezoresistivity; Vogit notation.

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1. Introduction

Smart structures are those structures, which sense the strain and alter their configurations according to the varying environmental conditions. In the past decade, modelling and controlling of smart structures has been the subject of intense research. During the past few years, a lot of work has been done using piezoelectric materials such as PZT, PVDF etc. as sensors and actuators in smart structures. Conventional sensors like strain gauge, piezoelectric and piezoresistive strain sensors have many limitations to be used as strain sensors. Prominent limitations include low sensitivity, high excitation voltage and high mass density. Because of the limitations of the conventional sensors, microelectromechanical (MEMS)-based strain sensors have attracted a lot of attention. MEMS carbon nanotube strain sensors [1] possess a very high gauge factor (200) and are suitable for low-power applications. It can work on several sensing principles of piezoresistive, piezoelectric, capacitive and optical properties. Out of all these, piezoresistive strain sensors are found to be more attractive because of their high sensitivity and low input power requirement.

In this paper, highly sensitive MEMS-based multiwalled (MWCNT)/epoxy strain sensor has been designed using COMSOL Multiphysics Toolbox. This sensor comprises su-8 epoxy as a base and MWCNT/epoxy as an active sensing element. MWCNT, when combined with epoxy, possesses large aspect ratio and high Young's modulus of elasticity. Due to larger aspect ratio, more conductive network is formed, resulting in higher strain sensitivity. This paper also discusses the process flow for fabricating MWCNT/epoxy thin film of uniform thickness.

2. MWCNT/epoxy strain sensor

In a MEMS-based U-shaped cantilever beam, stress is not uniformly distributed; it is maximum at the anchor side compared to the other side of the beam. So, to get the highest strain sensitivity, 2% weight MWCNT/epoxy thin film synthesized by using high shear mixing is deposited at the highest stress region, i.e. at the anchor of the cantilever beam. When stress is applied to a cantilever beam, it deflects which in turn changes the resistance of CNT film which is measured by Wheatstone bridge, i.e., connected to the gold metal pad of the sensor. The change in resistance with respect to strain shows that strain sensitivity is maximum when the concentration of MWCNT is close to the percolation threshold. The proposed design of MEMS-based MWCNT/epoxy is shown in figure 1.

2.1 *Piezoresistivity of MWCNT/epoxy thin film*

Strain sensing performance of CNT is due to its piezoresistive behaviour. Piezoresistivity means that the

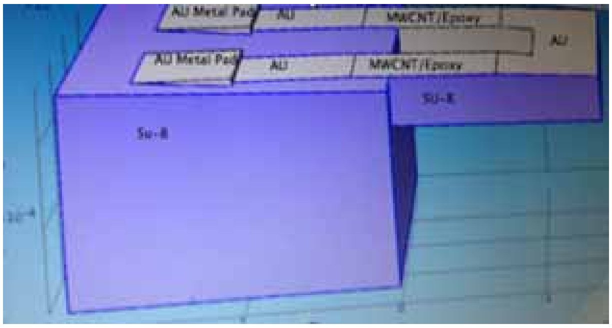

Figure 1. Device structure of MEMS-based 2% wt MWCNT/epoxy composite strain sensor in COMSOL Multiphysics Toolbox.

electrical properties of CNT changes with the mechanical deformation. Higher the value of change in resistance with respect to the applied strain, higher will be its sensitivity. The sensitivity of CNT strain sensors occurs in a wide range and it depends on various parameters such as percolation threshold, synthesis process, type of CNT and polymer used. In literature, it has been found that the strain sensitivity of CNT composite is higher than the pristine CNTs such as MWCNT and single-walled CNT (SWCNT). Out of all the nanocomposites, MWCNT/epoxy possesses the highest strain sensitivity. To achieve the highest strain sensitivity, the concentration of MWCNT in nanocomposite is kept close to percolation threshold (i.e. 2%). To design a highly sensitive MEMS-based strain sensor, 2% wt MWCNT/epoxy composite thin films are chosen as piezoresistors [2].

2.2 *Process flow for synthesizing MWCNT/epoxy thin film*

The process flow for synthesizing 2% wt randomly mixed MWCNT/epoxy composite thin film of uniform thickness (100–130 μm) involves the following steps [3]:

(i) First, a few grams of epoxy and 2% wt. of MWCNT are added in planetary mixer jar and mixed at a speed of 2000 rpm for a few minutes and then degassed in a vacuum oven (100 kPa) for a few hours at around 100°C .

(ii) One part hardener as the curing agent in 4 parts epoxy is added and shear mixed for a few seconds at the same mixing speed of 2000 rpm.

(iii) 2% wt. MWCNT/epoxy composite mixture is then poured into the mould and cured at around 30 MPa (at room temperature) for 24 h followed by post curing at around 70°C for a few hours.

(iv) To fabricate thin films, MWCNT/epoxy composite mixture is poured on a glass slide template.

(v) To obtain uniform film thickness, the poured mixture is then spread on the template by using either draw down processing, spin casting or hot pressing.

(vi) Finally, a thin film with uniform thickness of 100 to 130 μm will be prepared after curing at room temperature for a few hours followed by post curing at around 70°C for a few hours.

2.3 *Design of the sensor*

SU-8 [4] is used in the development of MEMS-based devices. su-8 is a negative photoresistor which can easily pattern multilevel structure. It is compatible with most of the micropatterning techniques such as UV-photolithography, e-beam lithography, laser and thermal ablation etc. Hence, in the proposed MEMS-based CNT strain sensor, su-8 material has been chosen for fabricating the cantilever beam. To design a highly sensitive strain sensor, geometrical dimensions of the cantilever and type of piezoresistors play crucial roles [5]. The proposed design comprises 200 $\times$ 200 $\times$ 130 μm cubic block of su-8 with a freestanding U-shaped su-8 cantilever beam of 250 $\times$ 50 $\times$ 30 μm dimensions. The U-shaped cantilever is preferred, as it is more sensitive in comparison to T and L-shaped cantilever beams [6]. Sensitivity of strain sensor increases on reducing the thickness and increasing the length of the cantilever beam [7]. So, the geometrical dimensions of the cantilever [8] must be optimized to achieve the highest strain sensitivity. In this proposed design, 2% wt MWCNT/epoxy thin film of uniform thickness has been chosen as active sensing elements. The location of piezoresistor also affects the sensitivity of the strain sensor. Strain is not uniformly distributed across the cantilever and it is found in literature that strain is maximum at the anchor of the cantilever beam. So, to achieve the highest strain sensitivity, nanocomposites are deposited at the anchor of the cantilever beam. To measure the change in resistance of piezoresistors with respect to mechanical deformation, two metal pads of Au electrodes of size 60 $\times$ 60 μm with 100 nm thickness have also been integrated in the design.

2.4 *Mathematical modelling*

Consider an external force applied at the tip of the one-dimensional cantilever beam; it results in a deformation of beam. For a given material, applied force is linearly related to deformation by Hooke's law, i.e.,

$$\sigma = E\epsilon, \tag{1}$$

where σ is the stress, ϵ is the strain and E is the modulus of elasticity, which depends on the type of material. For

Table 1. Basic material properties of the proposed design.

Material	Young's modulus E (GPa)	Poisson's ratio ν (dimensionless)	Density ρ (kg/m^3)
SU-8	2	0.22	1200
2% wt MWCNT/epoxy	2.4	0.33	1100
Au	70	0.44	19,300

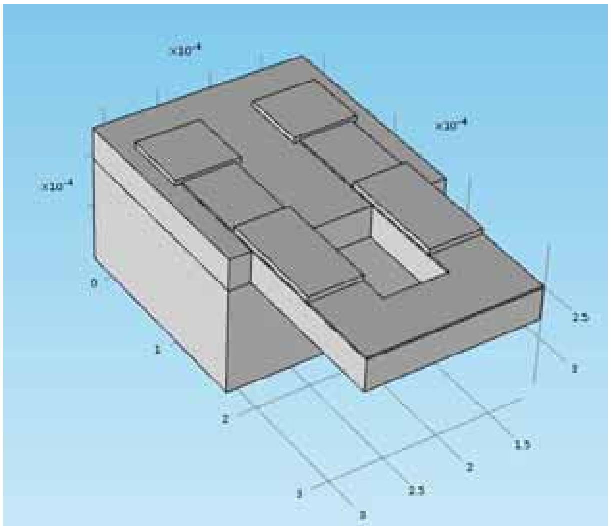

Figure 2. Imported geometry of MEMS strain sensor designed in solidworks into COMSOL Multiphysics Toolbox.

any three-dimensional linear anisotropic elastic material, generalized Hooke's law [9] is given by

$$\begin{pmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \zeta_{xy}\\ \zeta_{yz}\\ \zeta_{zx}\end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16}\\ c_{21} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26}\\ c_{31} & c_{32} & c_{33} & c_{34} & c_{35} & c_{36}\\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} & c_{46}\\ c_{51} & c_{52} & c_{53} & c_{54} & c_{55} & c_{56}\\ c_{61} & c_{62} & c_{63} & c_{64} & c_{65} & c_{66}\end{pmatrix} \begin{pmatrix}\epsilon_{xx}\\ \epsilon_{yy}\\ \epsilon_{zz}\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{zx}\end{pmatrix}. \tag{2}$$

In Vogit notation [9], strain and stress tensor is represented respectively as

$$\begin{pmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{pmatrix} = \begin{pmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \zeta_{xy}\\ \zeta_{yz}\\ \zeta_{zx}\end{pmatrix}$$

and

$$\begin{pmatrix}\epsilon_1\\ \epsilon_2\\ \epsilon_3\\ \epsilon_4\\ \epsilon_5\\ \epsilon_6\end{pmatrix} = \begin{pmatrix}\epsilon_{xx}\\ \epsilon_{yy}\\ \epsilon_{zz}\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{zx}\end{pmatrix} \tag{3}$$

$$\begin{pmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{pmatrix} = \begin{pmatrix} \lambda+\mu & \lambda & \lambda & 0 & 0 & 0\\ \lambda & \lambda+\mu & \lambda & 0 & 0 & 0\\ \lambda & \lambda & \lambda+\mu & 0 & 0 & 0\\ 0 & 0 & 0 & \mu & 0 & 0\\ 0 & 0 & 0 & 0 & \mu & 0\\ 0 & 0 & 0 & 0 & 0 & \mu\end{pmatrix} \times \begin{pmatrix}\epsilon_1\\ \epsilon_2\\ \epsilon_3\\ \epsilon_4\\ \epsilon_5\\ \epsilon_6\end{pmatrix} \tag{4}$$

$$(\sigma_i) = (c_{ij})(\epsilon_j), \qquad i, j = 1\text{–}6, \tag{5}$$

where (c_{ij}) is the compliance matrix of the anisotropic material with 21 independent elastic constants, Lame's parameters λ and μ are given by

$$\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)}, \tag{6}$$

$$\mu = \frac{E}{(1+\nu)}, \tag{7}$$

where ν is the Poisson's ratio of a given material. For the piezoresistive analysis of the proposed design, compliance matrix for each material used in the design must be calculated by using eqs. (5)–(7). To calculate the compliance matrix of the used material, the properties depicted in table 1 are required.

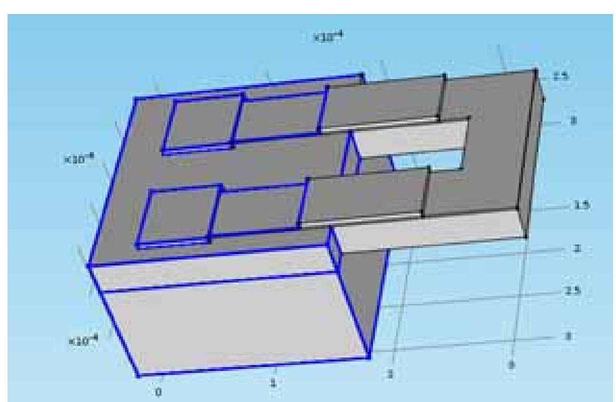

Figure 3. Fixed constraint region of the imported geometry highlighted by dark blue boundaries in COMSOL Multiphysics Toolbox.

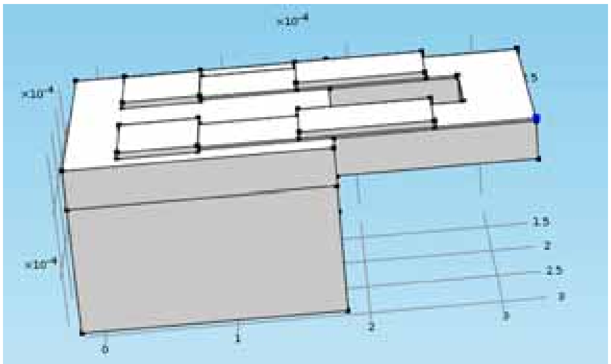

Figure 4. Point load at the tip end of the cantilever beam indicated by dark blue node in COMSOL Multiphysics Toolbox.

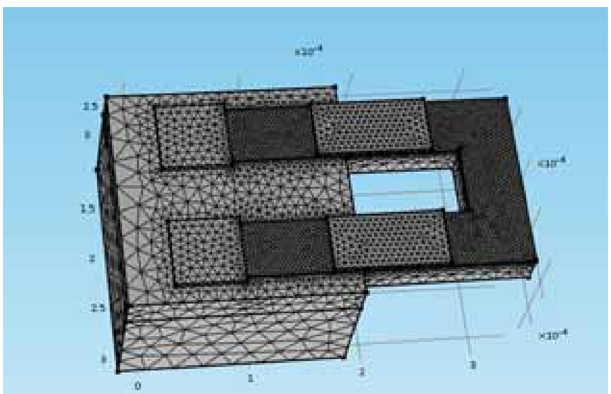

Figure 5. Fine meshing of the entire geometry of the device for finite element analysis.

3. Simulation and analysis of the proposed sensor

In the proposed design of the sensor, device geometry is designed in Solidworks and it is then imported in COMSOL Multiphysics Toolbox as shown in figure 2. After importing the geometry, next step is to assign different materials to different layers in material browser. Materials are assigned by using the properties defined in table 1. Once the materials for different layers are defined, next step is to fix the constraint in the device as shown in figure 3. After fixed constraint in the geometry, next step is to apply a point load of a few μN in z-direction at the tip end of the cantilever beam as shown in figure 4. The device geometry must now be fine meshed to do the finite element analysis of the design as shown in figure 5. After meshing, the final step is to compute the stationary study to obtain the total surface displacement in μm for a given load as shown in figure 6. Simulation result of the MEMS MWCNT/epoxy strain sensor in figure 6 showed a maximum total surface displacement of 14 μm for a given load.

4. Conclusion

This paper demonstrated an optimized design of highly sensitive MEMS-based MWCNT/epoxy strain sensor using COMSOL Multiphysics Toolbox. This paper has also reported the process flow for synthesizing 2% wt MWCNT/epoxy thin film of uniform thickness. Simulation result has proved that the proposed design can serve the purpose of highly sensitive strain sensor. In future, eigenfrequency analysis can also be done to obtain the region of resonant and natural frequencies of the proposed device.

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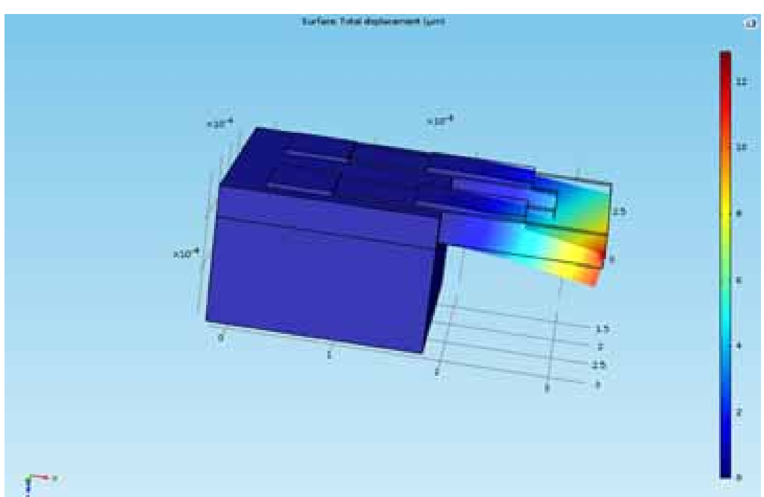

Figure 6. Simulation result of the total surface displacement of a device (in μm) for a given point load at the tip end of the cantilever beam in COMSOL Multiphysics Toolbox.

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