Development and performance evaluation of self adhesive sputtered thin film strain gauges

Shreyas P. Bhat[1,2*], B. Pavithra[1], S. H. Bharathi[2], M. M. Nayak[1]

[1] *Indian Institute of Science, Bengaluru, India*
[2] *REVA University, Bengaluru, India*

Presented in National Conference on Micro System Technology (NCMST-2020), CMTI, March 4-6, 2020.

KEYWORDS

Thin Film,
Thin Film Strain Gauge,
Self-Adhesive,
Sputtering,
Piezoresistivity,
ITO,
NiCr.

ABSTRACT

In many industrial and academic applications force, pressure and displacement are measured using strain gauges bonded with adhesives on the object to be tested. This paper presents development and performance investigation of non-intrusive self adhesive Thin Film Strain Gauges (TFSGs) for applications demanding quick gauge installation on test objects; eliminating a conventional step of applying adhesives for installation and curing. Self adhesive TFSGs of NiCr (metal alloy) and ITO (degenerate semiconductor) are fabricated. Distinction in the piezoresistive responses and gauge factor of metal alloy and degenerate semiconductor thin film strain gauges are measured and studied by cantilever beam bending method.

1. Introduction

Strain gauges based on the detection of small resistance variations due to load or force or displacements are universally recognized as piezo-resistive sensors. It is one of the simplest, most common and most investigated classes of sensors; hence continuous efforts are focused on improvement of devices with high performance that can be employed in commercial and academic applications like evaluation of strain, force, pressure, acceleration [1].

In the last few decades, there has been an increase in interest on the study of thin films as strain sensing elements. Because of the versatility of thin film technology it is possible to fabricate devices of desired specification and properties. An added advantage of employing thin film technology for strain gauge production is that it can be used in mass production with considerable cost reduction. Continuous metal and metal alloy films have gauge factor around 2-6 [2, 3]; whereas ultrathin metal films with high sheet resistance are often discontinuous, hence exhibits higher value of gauge factor ranging from few tens to hundreds, depending on the material(s) used [4]. But discontinuous films however, are not used extensively because of lack of repeatability and poor performance stability.

*Corresponding author,
E-mail: shreyasbhathere@gmail.com

Strain gauges are usually fabricated on a thin polymeric flexible backing material, usually polyamide, which are electrically insulating. They merely serve as mechanical carrier for the strain sensing layer(s) deposited on it. The measurements using strain gauge assumes that the strain on test object is faithfully transferred without any loss. This requires very tight bond between strain gauge and object under test. The very close bonding which is needed between the measurement object and the strain gauge is best provided by bonding adhesives recommended by strain gauge manufacturers. For any commercial application or academic purpose, the need of applying and curing adhesives can be eliminated by employing self adhesive strain gauges; wherein the a thin adhesive layer made of silicone is already present on one side of the substrate. It can then be attached to test object surface with light pressure (finger pressed) for quick installation. The present investigation is aimed at understanding the feasibility of self adhesive thin film strain gauges for academic, research and industrial applications. Self adhesive strain gauges can be readily attached to the specimen of interest. This avoids one intrusive yet crucial step of uniformly applying bonding adhesive on TFSG to attach on to test specimen and cure at the temperatures as per manufacturer's recommendation.

2. Experimental Method

a). Fabrication of strain gauges

Flexible polyethylene terephthalete (PET) substrate (130 µm thick) with thin silicone adhesive layer on one side is used to fabricate piezo-resistive TFSGs. Glass substrate is used as backing for PET substrate for ease of fabrication processes. Substrates are solvent cleaned prior to the processing. Direct writing technique is employed to create uniaxial meandering patterns on self adhesive substrates. DC magnetron sputtering technique is employed to deposit strain sensing layer(s) on the patterned samples. Nickel Chromium (Ni:Cr 80:20) alloy target is used to fabricate metal TFSG and Indium Tin Oxide (In_2O_3:SnO_2 90:10) target is used to sputter degenerate semiconducting TFSG on PET substrates, at room temperature.

Since the bulk resistivity of NiCr and ITO alloy are high in the range of 10^{-3} to 10^{-4} Ω.cm, the sputtered films must be thicker than 1 µm to achieve gauge resistance less than 5 K.Ω (for the gauge dimensions patterned). Residual tensile stress exhibited by NiCr when sputtered on polymeric substrate at room temperature results in cracking of film surface when the film thickness exceeds 250 nm (figure 1). A thin conductive layer of resistivity ~10^{-6} Ω.cm (Au or Ag) is thus sandwiched between NiCr and ITO layers to yield low gauge resistance for thin continuous films. After sputtering sensing layers, photoresist on PET is stripped off in solvent. Sputtered film(s) stack had excellent adhesion to PET substrate. Thin copper leads are bonded to the contact pads on TFSGs using silver epoxy.

b). Characterization and testing of strain gauges

Once the TFSGs are fabricated, they are transferred from the glass backing onto a test specimen of known dimension. The PET substrates serve as a brilliant insulation between stainless steel (SS) test specimen and resistive sensing grids. Electrical insulation exhibited by PET substrate is greater than 9999 MΩ at 50 volts DC.

Cantilever bending method is adopted to evaluate the responses of TFSGs attached to stainless steel specimens. To study device response to the longitudinal tensile stress, bending moment is applied to the cantilever beam by fixing one end of the test specimen to a mechanical wise and deflecting the other end progressively using a height gauge. The known deflection of the beam is then converted into respective force and strain values. The change in the resistance of the gauge at each increment and decrement of strain are recorded to understand the hysteresis. The test specimen for metal TFSG is 30 mm long, 26 mm wide and 0.5 mm thick and that of semiconductor TFSG is 44 mm long, 26 mm wide and 0.1 mm thick.

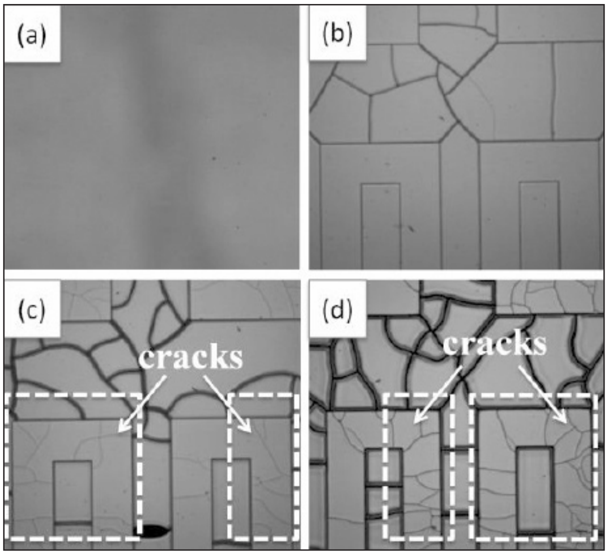

Fig. 1. Optical micrographs of (a) substrate surface, (b) 250 nm NiCr film, (c) 500 nm NiCr film and (d) 1000 nm NiCr film sputtered on patterned substrate.

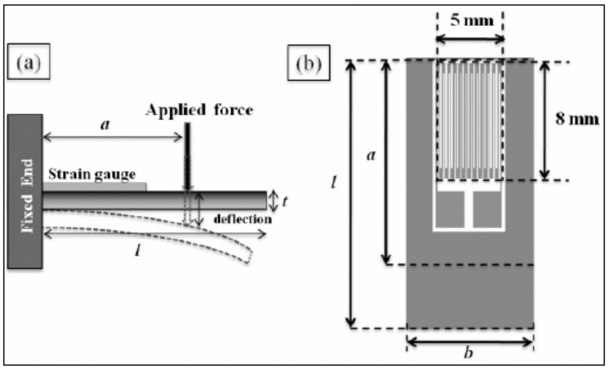

Fig. 2. (a) Schematic representation of cantilever bending test setup (cross sectional view) and (b) TFSG attached to SS specimen.

Two separate measurements are carried out. In the first set, resistance measurements are made with TFSGs attached to different SS specimens, "as it is" (without additional adhesive). In the second set, TFSGs are attached to SS specimens using M-Bond 200 adhesive, which gets cured instantly at room temperature. All measurements are performed in air ambient, at room temperature.

3. Results and Discussions

Self adhesive TFSGs possess the advantage of sticking uniformly on low energy surface (like plastic) and also energy surface (like metals). The adhesive/sticky layer is made of polysiloxanes (also called silicone), and are transparent in the visible wavelength. Repositioning with clean removability, ability to move trapped air bubbles between substrate and test object after TFSG attachment, and resistance to solvents are few of the advantages using self adhesive substrates.

a). Piezoresistive response

The cantilever beams are deflected to a maximum of 1000 µm corresponding to 1330 µƐ for metal TFSG (NiCr/Au/NiCr) and 171 µƐ for semiconductor TFSG (ITO/Ag/ITO). Beam deflection causes change in length (Δl) of SS test specimen attached to strain gauge. If the direction of the strain coincides with geometrical dimension of the strain gauge (usually length for uniaxial gauge) then the change in resistance (ΔR) can be related to change in length of the strain gauge. Change in resistance is observed for TFSGs made of both materials in its self adhesive setup as well as bonded setup of measurement. The resistive response (ΔR/R) of metal TFSGs are in the order of 10^{-3} to 10^{-4}, and for semiconductor TFSGs in the order of 10^{-4}.

The plot in the inset of figure 3 and 4 shows the experimental stress-strain relationship in the proportional limit (elastic behavior regime) of the stainless steel specimens, to avoid permanent deformation when the forces are withdrawn.

Hysteresis characteristics of resistance change (ΔR/R) as a function of applied strain (Ɛ) is shown in fig 3 and 4. When an object attached to strain gauge undergoes deformation, the strain is transferred from the measurement object to the adhesive layer, then from the adhesive layer to the sensing layer carrier and at last from the carrier to the sensing layer. The tensile strain causes the resistance of the gauge to increase; therefore the ΔR/R is positive. The migratory nature of silicone in the adhesion layer of self adhesive TFSG causes inconsistency in the change of resistance with imposed strain on test specimen. Silicone migration is due to low surface energy substance (silicone) in contact with a higher energy surface (stainless steel specimen) [5]. Hence it restricts efficient transfer of strain from the

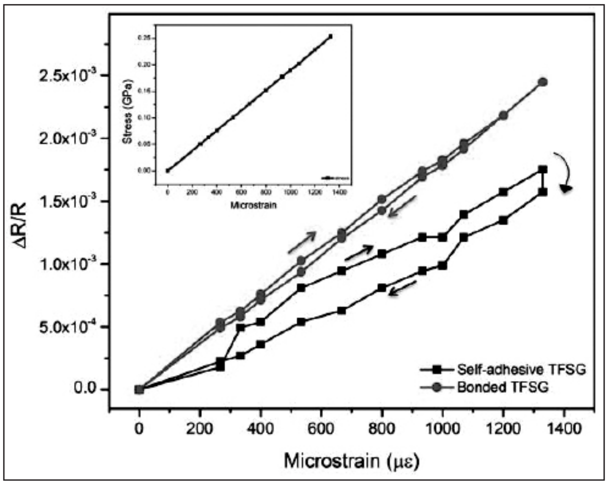

Fig. 3. Relative change in resistance as a function of strain for NiCr/Au/NiCr TFSG.

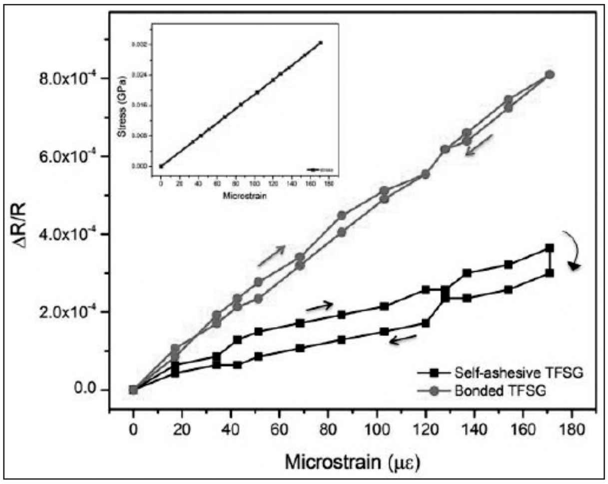

Fig. 4. Relative change in resistance as a function of strain for ITO/Ag/ITO TFSG.

Table 1
Thin film strain gauge data.

Device name	Film stack	Thickness (nm)	Device resistance (KΩ)	Adhesion type
1A	NiCr/Au/NiCr	100/20/100	2.22	Self-adhesive
1B			2.24	Bonded
2A	ITO/Ag/ITO	50/10/50	4.66	Self-adhesive
2B			4.68	Bonded

strained specimen to the resistive sensing layer. Therefore, the hysteresis in silicone based adhesion is more for metal and semiconductor TFSGs on self adhesive substrates. ΔR/R improves considerably (fig 3 and 4), when TFSG is attached to SS specimen using M-Bond adhesive, due to tighter bonding of substrate with specimen resulting in better strain transfer. But, the presence of silicone particles with M-Bond adhesives results in slight hysteresis during measurements.

b). Strain sensitivity

The strain sensitivity of the gauges can be calculated by measuring the change in relative resistance for a known amount of strain on object under test. The measure of sensitivity of the strain gauge is called gauge factor. Generally, NiCr metal strain gauge exhibits gauge factor around 2 [3], and that of ITO strain gauges around -4 to 7 [6], depends on the material composition in the sensing layer.

The beam deflection is converted into applied force by the physical relation given by equation 1,

$$F = \frac{6Ebt^3(Deflection)}{12a^2(3l-a)} \quad (1)$$

Stress and strain on the specimen are calculated by the relation in equation 2 and 3, respectively.

Young's modulus of stainless steel is 190 GPa.

$$\sigma = \frac{6Fa}{bt^2} \quad (2)$$

$$\mathcal{E} = \frac{\sigma}{E} \quad (3)$$

σ= stress on the beam, Ɛ= (Δl/l) strain on the beam, E= Young's modulus of SS specimen, F= force applied, l= length of the beam,

a= length of beam from fixed end to point of force applied,

t= beam thickness, b= beam width

The application of strain to semiconductor film leads to a change in the shape of the Brillouin zones in the lattice. This in turn leads to a change in average electron velocity which changes its mobility and hence the resistance changes [7]. The gauge factor of ITO based TFSG is found to be in the range of 1.5 to 3 when attached "as it is" and effectively increase to the range of 4.6 to 5.4 for its bonded counterpart as seen in figure 6. This effect is relatively small in metals due to the relatively large number of free electrons and therefore, the gauge factor of continuous metal film is generally very small ~1 to 2. The gauge factor of metal TFSG is found to be in the range of 0.6 to 1.3 when attached "as it is" and gauge factor of 1.7 to 2 for its bonded counterpart, shown in figure 5.

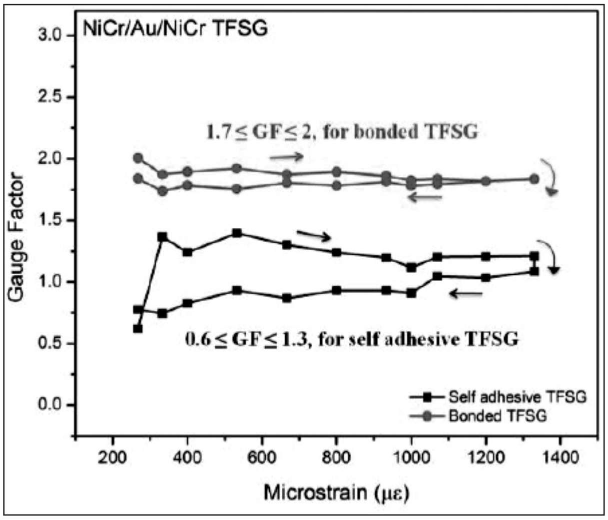

Fig. 5. Gauge factors of NiCr/Au/NiCr TFSG with applied strain.

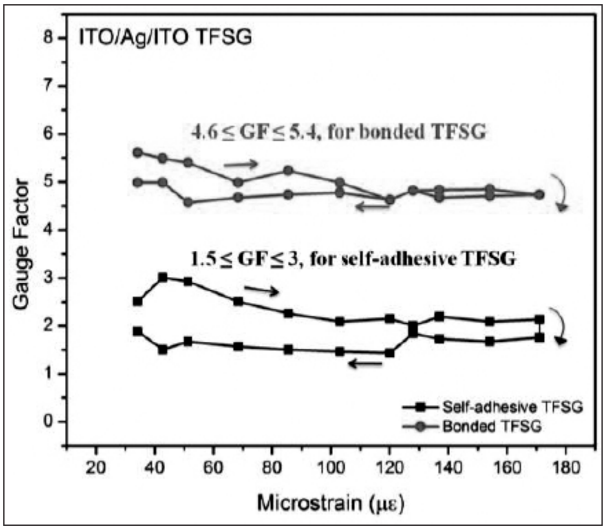

Fig. 6. Gauge factors of ITO/Ag/ITO TFSG with applied strain.

c). Repeatiblity and stability

Repeatability of resistive responses of self adhesive and bonded TFSGs are shown in figure 7. Silicone layer as bonding agent in self adhesive TFGS does not solidify to form solid interfacial

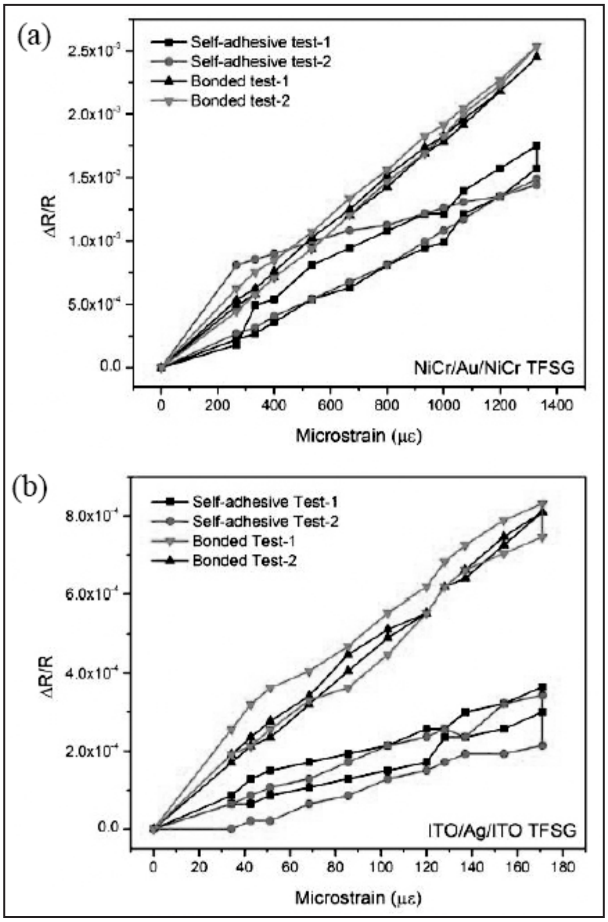

Fig. 7. Repeated resistive responses of self adhesive and bonded- (a) NiCr/Au/NiCr TFSG and (b) ITO/Ag/ITO TFSG.

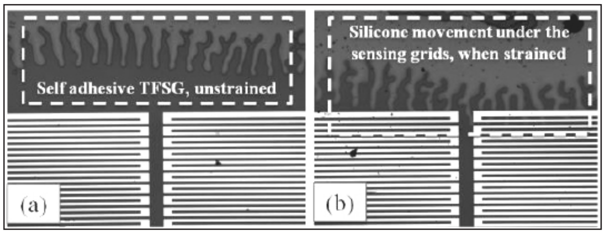

Fig. 8. Optical micrographs of self adhesive TFSG in (a) unstrained, and (b) strained condition, showing viscous nature of silicone adhesive under strain sensing grids.

bond between PET backing and SS specimen, but remain viscous. Variation in ΔR/R as a function of strain applied to self adhesive TFSG in the second testing cycle can be attributed to the migratory nature of viscous silicone on the strained specimen as seen in optical micrographs of TFSGs when unstrained and after application of strain, in figure 8. By applying M-Bond 200 adhesive over the already present silicon layer on PET, resistive response of TFSGs improves considerably. The hysteresis reduces with strain increment and decrement test cycles. Slight hysteresis observed in measurement with bonded TFSGs is due to presence of un-solidified silicone particles within the solid adhesive interface formed by applying M-Bond 200 between PET substrate and specimen.

4. Conclusion

In this work, development, fabrication and testing of metal alloy and degenerate semiconductor based self adhesive thin film strain gauges on PET substrates were demonstrated. Longitudinal strain responses were measured for NiCr/Au/NiCr and ITO/Ag/ITO sputtered TFSGs installed on SS specimens. The gauge response was found to be non-linear for self-adhesive TFSGs due to the migratory behavior of silicone in adhesion layer on the application of strain. The transfer of strain from the specimen to sensing layer is found to be notably lesser on self-adhesive TFSGs when compared to its bonded counterpart. The factors affecting consistency of self adhesive TFSGs were discussed. Self adhesive TFSGs possesses advantage of repositionability and adhesion to almost all surfaces, thus can be employed in non-linear and non-intrusive sensing applications, which demands quick installation of strain sensors in ambient condition to measure impact and strain.

5. Acknowledgement

The authors would like to acknowledge the funding support from MeitY and DST Nano Mission through NNetRA. We acknowledge the National Nanofabrication Centre (NNFC) and Advanced Packaging Lab at Centre for Nano Science and Engineering, Indian Institute of Science for usage of the facility.

6. References

1. Fiorillo, A. S., Critello, C. D., & Pullano, A. S. (2018). Theory, technology and applications of piezoresistive sensors: A review. *Sensors and Actuators, A: Physical,* 281, 156-175. https://doi.org/10.1016/j.sna.2018.07.006

2. Kalpana, H.M., and Prasad, V.S. (2014). Development of the invar36 thin film strain gauge sensor for strain measurement. *Measurement Science and Technology,* 25(6), 065102. *DOI: 10.1088/0957-0233/25/6/065102*

3. Kazi, I.H., Wild, P.M., Moore, T.N. & Sayer, M. (2003). The electromechanical behavior of

nichrome (80/20 wt.%) film. *Thin Solid Films,* 433(1-2), 337-343. https://doi.org/10.1016/S0040-6090(03)00390-0

4. Lee, T., Choi, Y.W., Lee, G., Pikhitsa, P. V., Kang, D., Kim, S.M., & Choi, M. (2016). Transparent ITO mechanical crack-based pressure and strain sensor*. Journal of Materials Chemistry C*, 4(42), 9947–9953. https://doi.org/10.1039/c6tc03329f

5. Meyer, J., Smith, C.A. (2012*). Effect of silicone contamination on assembly processes.* 3, 1622-1642.

6. Gerdes, H., Bandorf, R., Heckmann, U., Schmidt, V., Kricheldorf, H. U., & Bräuer, G. (2009). Sputter deposition of strain gauges using ITO/Ag. *In Plasma Processes and Polymers*, 6(S1), S813-S816. https://doi.org/10.1002/ppap.200932101

7. Witt, G.R. (1974). The electromechanical properties of thin films and the thin film strain gauge. *Thin Solid Films,* 22(2), 133–156. https://doi.org/10.1016/0040-6090(74)90001-7

8. Siddall, G., & Smith, G. (1959). A thin film resistor for measuring strain. *Vacuum,* 9(2), 144-146. https://doi.org/10.1016/0042-207X(59)90730-4

Shreyas P. Bhat is working as Facility Technologist with the National Nano fabrication Centre, Centre for Nano Science and Engineering, Indian Institute of Science, Bengaluru, India. He has over four years of experience in semiconductor device fabrication with expertise in Thin film deposition and lithography. He received the B.E degree in Electronics and Communication Engineering from Visvesvaraya Technological University and M.Tech degree in VLSI & embedded system from REVA University.

Pavithra B. is presently working as Project Assistant, Centre for Nano Science and Engineering, Indian Institute of Science Bengaluru, India. She is a graduate B.E in Electrical and Electronics Engineering from SDMIT Ujire, Karnataka, India in 2012. The M.Tech degree in VLSI Design and Embedded System from NMIT in 2020. She has seven years of research experience in the MEMS and testing of the pressure sensors. She has published one international journal, 4 conference papers and one patent has been filed.

Dr. Bharathi S.H. presently serves as Professor in REVA University, Bangalore. She has over 28 years of teaching and 5 years of research experience. She has published over 34 papers in national/international journals and conferences. She received her Ph.D from Sri Krishnadevaraya University in 2013. She is actively involved in research and projects related to signal processing and image processing.

Dr. M.M. Nayak received his Ph.D from Indian Institute of Science, Bangalore in 1994. He served in Indian Space Research Organization, Department of Space for nearly 40 years in various capacities. During his service, he developed and led production of space qualified pressure transducers for PSLV, GSLV, GSLV M3, IRS, INSAT, Chandrayaan missions. He is a recipient of several prestigious awards, has over 81 publications and 9 patents. He is presently an Emeritus Professor at Centre for Nano Science and Engineering, IISc, Bangalore, further pursuing his research activities in MEMS and sensors for defense and aerospace applications.