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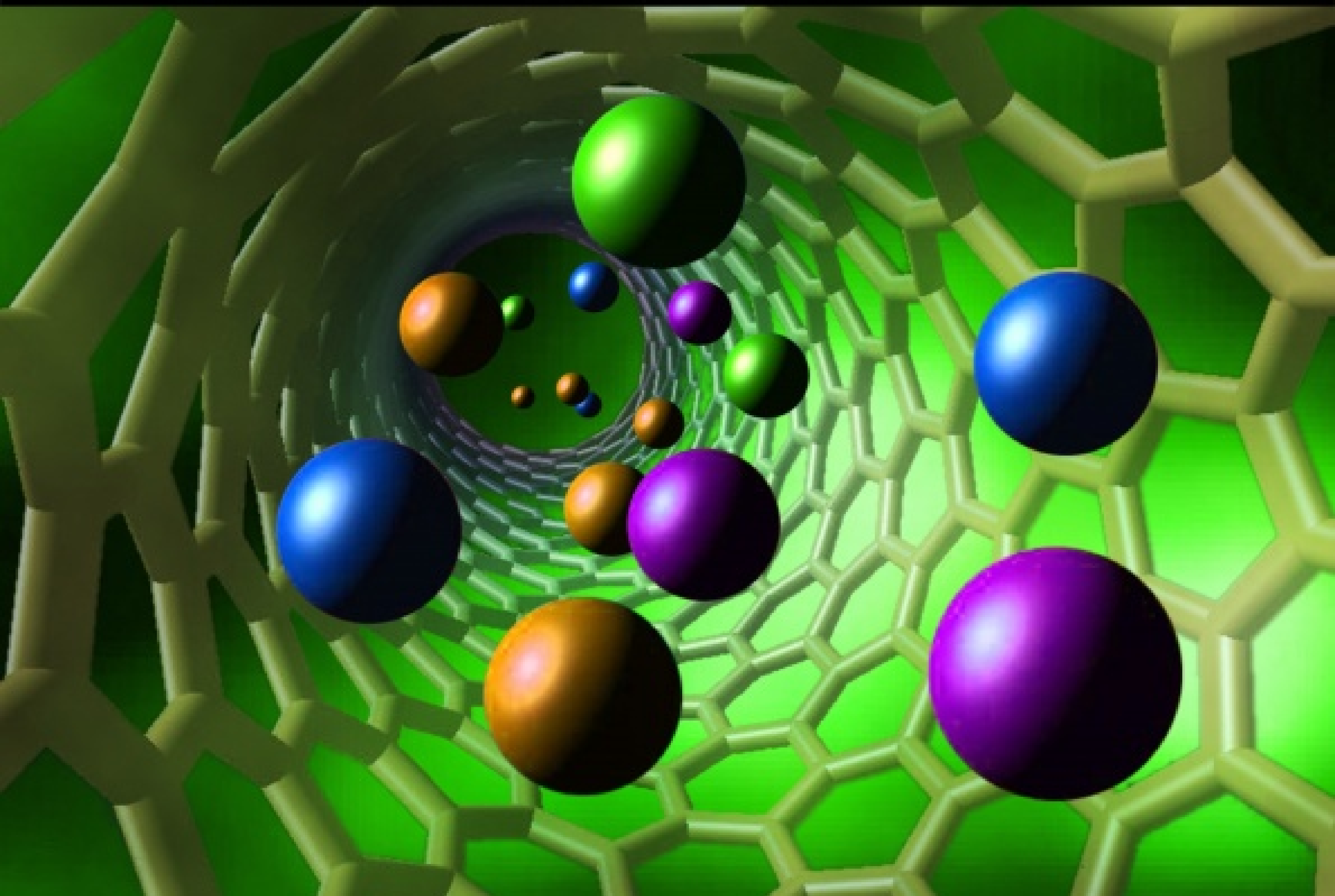

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Flexible Membrane Impact Sensor via Thick Film Method

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Abstract: A piezoresistive based impact or contact sensor on flexible polyimide substrate is constructed with pressure sensitive electrically conductive polymer composites with a Shore "A" hardness of 78 and nano silver inks using thick film method. Optimum design layouts of the sensor's electrode pair spacing of the polymer based impact sensor are modeled. The transducer resistance change has an exponential decay relationship upon external impulse activation. A shock and vibration test bench is build to test the fabricated impact sensors. The loading time dependence of the conductive polymer transducer electrical resistance at constant pressure is investigated. The conductive polymer transducer electrical resistance response is found to be stabilized after about 6 sec. A theory is also formulated to explain the observed negative exponential response. An environmental chamber is used to test the conductive polymer transducer's thermal response in the cycling range of 25^{o}C to 80^{o}C. *Copyright © 2007 IFSA.*

Keywords: Flexible substrate, Impact sensor, Membrane

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1. Introduction

Transported apparatus or materials regularly experience mechanical shocks in the course of its functionality life cycle. The subjected physical shocks [1], however brief, from a fraction of a millisecond to a several milliseconds in duration, is frequently severe, damaging and cannot be overlooked [2]. If the shock is recurring many times, such as the shock recorded on air-dropped munitions and equipments or the landing gear of an aircraft, the fatigue damage accumulated in the structural elements can lead to fracture [3]. The shock induces transitory dynamic stress in structures. These stresses are a function of the characteristic of the shock i.e. amplitude, duration, and shape; and the dynamic properties of the structure i.e. resonant frequencies, Q factors.

Researchers have investigated cost efficient and less complex methods of producing rugged transducers to track force impulses or momentum variations. Besides the popular but expensive MEMS based accelerometer approach [4, 5], thick film [6] and drop coating [7] alternative technologies using highly conductive filler i.e. carbon black and surfactant is viable. Other conductive polymer based approaches [8,9] and the oscillating cantilever based approach [10, 11, 12] for shock and vibration sensor/transducer have been investigated.

This paper discusses an impact shock sensor constructed with pressure sensitive polymer layers on the flexible membrane polyimide substrate encapsulated with a layer of SiNx. The highly conductive Al electrodes are sputtered according to the modeled spacing between the pair. The electrical resistance changes of the conductive polymer strongly depend on the external applied stress. Upon any impacts the resistance of the active conductive polymer elements will change from > 500 MΩ to as low as 0.1 Ω if the pressure or force surpasses the designed/preset actuation pressure. The device's impulse threshold or sensitivity can be designed by varying the polymer thickness. Due the nature of the polymer, it can be used in harsh environments such as marine (salt water), outdoor (acid rain), rapidly fluctuating relative humidity and thermal shock conditions [13].

The experimental results and observations presented in this paper include 1) studies of the electrical resistivity changes with applied load; 2) prolonged external loading time effects; and 3) temperature dependency of the conductive polymer transducer.

2. Theory

According to the popular model derived in Ref. [14], the total changes of electrical resistance R of the polymer composite is calculated from the following relation;

$$R = (\frac{L}{N})(\frac{8\pi hs}{3a^2\gamma e^2})e^{\gamma s}, \tag{1}$$

where, L is the number of particles forming the single conductive network path, N is the number of the numbers of the conductive paths, h is the Planck's constant, s is the minimum spacing between the conductive particles, a^2 is the effective cross-sectional area, where the tunneling occurs, and e is the electron charge. γ is given by

$$\gamma = \frac{4\pi(2m\phi)^{1/2}}{h}, \tag{2}$$

where, m is the electron mass and ϕ is the potential barrier between adjacent particles

When a shock or impact is incident to the polymer shock transducer, the resistance will be altered because of the change of the conductive particle separation. Let the particle separation change from s_o to s with the applied forces, corresponding to the changes in resistance R_o to R.

The relative resistance is given by

$$\frac{R}{R_o} = (\frac{s}{s_o})e^{\gamma(s-s_o)} \tag{3}$$

with R_o and s_o is the initial resistance and initial particle separation respectively. The R_o of the conductive polymer is typically in the range of 30 MΩ.

For the case of the polymer composites under compressive strain, the sensor's under compression particle's separation, s, is shorter that the initial uncompressed particle's separation, s_o (i.e. $|s| << |s_o|$). Hence, the resistance under compression is lower than the initial uncompressed resistance as observed in the experimental results. It is also noted that the relationship observed (resistance vs. pressure) has the exponential function behavior similar to the theoretically derived model (negative exponential trends as exponential variables, $s-s_o$ is less than zero) and its coefficient's amplitude can never have negative values.

If a large enough stress or impact is applied that surpasses the polymer elasticity limit (shock limit), the sensor would have the characteristics of a "shorted" conductor as the particle separation is approximately equal to zero. This is recognizable and proved by letting the particle separation *s* equal to zero in the above Equation 3, and therefore *R* is practically equal to zero.

From the experiment, the following important facts are inferred:
1) Highly conductive nano-particles have to be chosen for a reversible and sensitive shock and vibration transducer.
2) A strong cross-linked synthetic polymer rubber must be selected for the elastic matrix.
3) Maximum bonding between the conductive nano-particle, elastic elastomer polymer and substrate must exist for stable transducer characteristics intended for harsh environments. However, the conductive polymer should not have any strong adhesive force between the conductive electrodes (metallic) and polymer interface.

3. Device Design and Realization

The fundamental designed layout of the polymer based impact sensor is as shown in Fig. 1. The sensor is design to take advantage of the flexibility and light weight of the membrane. In addition, the sensor has a very low profile with a max thickness of 0.59mm. Kapton E is selected as the transducer's substrate due to its thermal (high temperature stability) and processing tolerance (mechanical/shear modulus) properties [15]. It has been prepared and cut into 4" in diameter circular shapes followed by the standard 3x pre-clean cycles of 1hr iterations of boiling with M-clean cleaning agent, ultrasonic, and rinsing. After the regular cleaning procedure for the flexible Kapton E membranes, an O_2 plasma of 11W power via a Plasma Enhanced Chemical Vapor Deposition (PECVD) system is applied to modify the polyimide Kapton E surface roughness for better adhesion with the layer of SiNx encapsulation.

A layer of highly conductive Al electrodes is next sputtered using a Varian 3125 DC S-gun metal sputterer according to the specifically modeled pair spacing. The pairs of electrodes are next patterned using standard photolithography techniques and wet chemical etched with Aluminum etch bath. The electrode sizes are measured to be 0.7mm L with 0.3mm W with different electrodes spacing between them. The spacing is modeled using the electrical conductive model on Comsols Multiphysics software version 3.3a.

The shock/impact sensitive conductive polymer used for the impact sensor studies is made of highly elastic Zoflex FL75.1 liquid conductive rubber [13] and highly conductive Nanomastech nano-sized silver ink [16]. The composite's active elements have a "Shore A" hardness of 78 but are highly conductive due to the proper mixing rate and 1:6.63 chemical ratios. Its specific gravity is 2.1. For the measurements of the electrical resistivities changes as a function of applied load or pressure, several 3-D rectangular structures were made and prepared via stencil printing technique. The polymer samples of the dimension of 0.5 mm H X 6.84 mm W X 5.5 mm L for 2.6 mm electrode spacing and 0.5 mm H X 6.37 mm W X 12.91 mm L for the 4.8 mm electrode spacing are prepared. The polymer is cured at 25°C or 77°F for approximately 10 hours. Post-curing and annealing steps is also performed at 50°C for approximately 3 hours to reduce bulking and removal of contaminants such as amines, sulfur, and soaps.

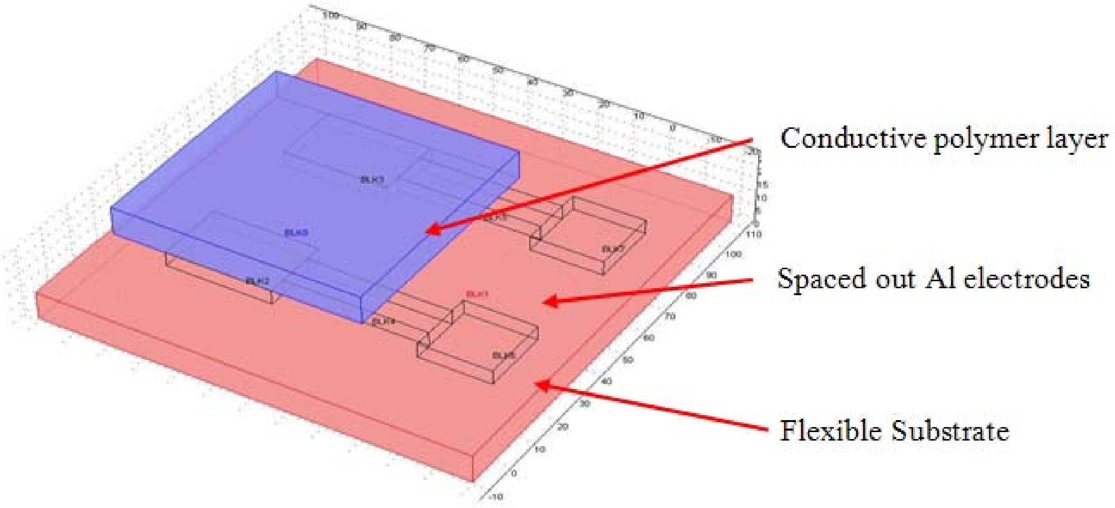

Fig. 1. Impact sensor's layout via FEM simulation.

The device is next wired with pure indium solder at 800°F via a tiny soldering iron tip and interfaced with the computer controlled digital multimeter (Protek 506 DMM digital multimeter). The device's electrical resistance is measured using a multimeter and interfaced with a LabVIEW program written for averaging, error minimization and storage. A shock and vibration test bench (Fig. 2) is build to test the fabricated impact transducer. The shock and vibration bench is capable of generating Sine or Saw-tooth waveforms. The frequency is varied with the use of the HP 33120A waveform generator. The shock and vibration test bench is also calibrated with an INTERFACE SMT-1-10N load cell. The maximum force that can be excited and feedback is 100N (overload) with a sensitivity of +/- 0.0005N. The load cell is interfaced to the PC data acquisition via a LabVIEW program. The LabVIEW program can monitor both the sensor response output and table movement or load.

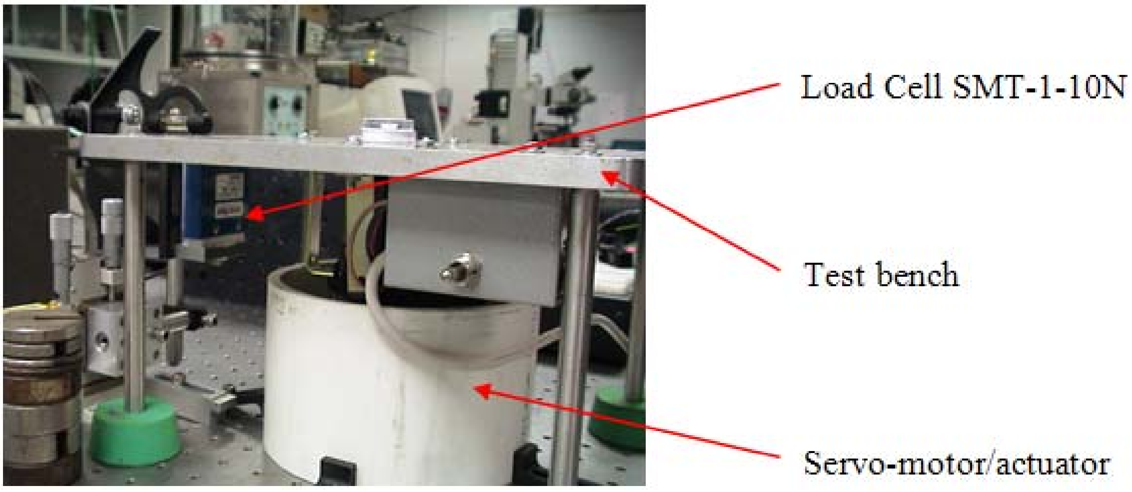

Fig. 2. Vibration test bench with load cell.

Fig. 3 shows the conductive polymer shock sensor being applied with 1000 grams load inside the sealed environmental chamber for thermal cycling experiments. Temperature range tested is from room temperature of about 25°C to 80°C (176°F) at 35% constant relative humidity.

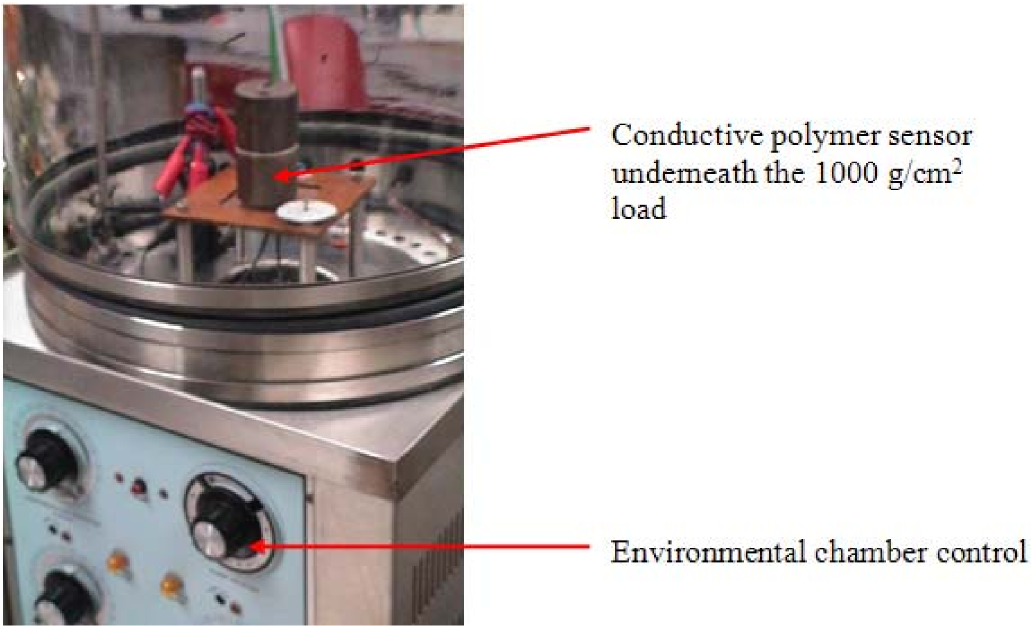

Fig. 3. Environmental chamber with conductive polymer transducer loaded with 1000 g/cm^2 during the thermal cycle experiments of 25°C to 80°C.

4. Results

The measured data of the conductive polymer transducer is plotted in Fig. 4. The electrical resistance is measure within 1 second after the application of each load. The electrical resistance of the samples changes by 6 orders of magnitude from the nominal 30 MOhm range to approximately 20 Ohm and subsequently returns to its initial value after the load is removed within/in less than 800 msec. These reversibility and the huge changes in electrical resistance under mechanical deformation by the loads are due to the higher mobility of the micro particles and the strong adhesion of the silver particles to the elastic polymer matrix [17]. For conductive polymer transducer's of 0.5mm thickness, the resistance output decays exponentially with external applied loads. When a shock or impact is incident to the sensor, the resistance will be altered because of the change of the conductive particle separation. The conductive polymer-based impact sensors exhibit fast resistivity transformation characteristics with external applied force/pressure.

Next, the time dependence of the conductive polymer transducer electrical resistance is investigated. A constant load of 1000 g/cm^2 or 14.22 psi is used in this experiment. The response is as shown in Fig. 5. The conductive polymer electrical resistance is measured for >5 min at a time but only the first 25 sec of activity is plotted since duration longer than the first 25 sec is a flat DC response. The sample cross sectional area is 1 cm^2 with a thickness of 0.5 mm. It is observed that the transducer's resistance response has a transient decay that mimics an un-normalized negative exponential function. The response is measured and averaged at a rate of 60 counts/sec using a Protek DMM 506 digital multimeter. The resistance stabilized after approximately 6 sec after the loading. The delay in response might be due to the sponginess or "Shore A" hardness mixture ratio (γ, reaction constant) coupled with the thickness of the used polymer.

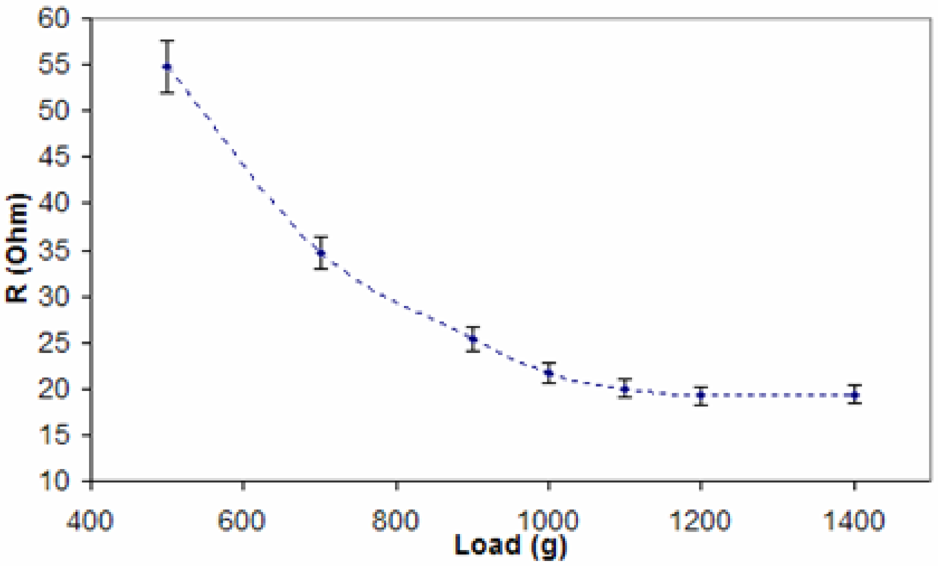

Fig. 4. Electrical resistance R (Ohm) decays exponentially with external applied load (grams). The sample thickness is 0.5 mm with contact area of 1 cm^2.

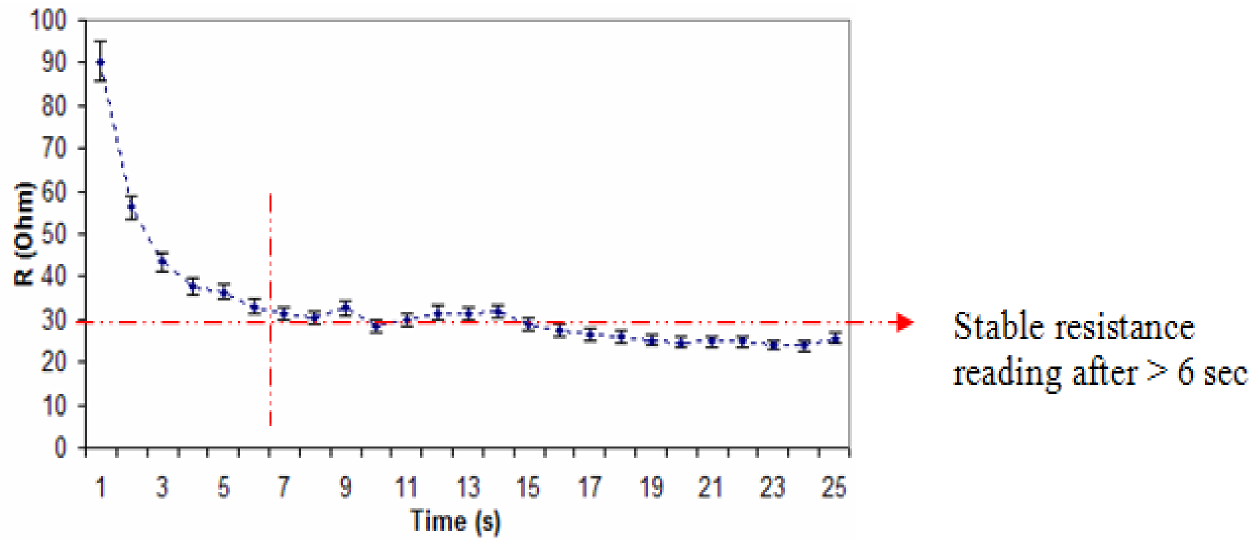

Fig. 5. Electrical resistance changes over time held under constant applied load of 1000 g/cm^2 or 14.22 psi. The sample thickness is 0.5 mm with contact area of 1 cm^2.

Next, the conductive polymer based impact sensor's outputs (i.e. resistance) are measured as a function of temperature after the resistance has stabilized from the typically loading time decay. This duration is inferred from the conductive polymer decay response in Fig. 5. The average wait time is approximately 8 sec. Moreover, during this period, the chamber temperature is well stabilized so that any transient temperature effects are minimized. Several sets of reading are measured before increasing the temperature to the next level. The electrical resistance as a function of temperature is as plotted in Fig. 6. A constant load of 1000 grams is used for this experiment. The conductive polymer transducer exhibits a very weak semimetals-like temperature dependence of resistance. Hence, this transducer can also serves as an elevated temperature monitor or fuse inside an enclosed body. However, it should be noted that thermal hysteresis effects are not measured/observed as cooling rates are not satisfactory controllable with the current version of the environmental chamber.

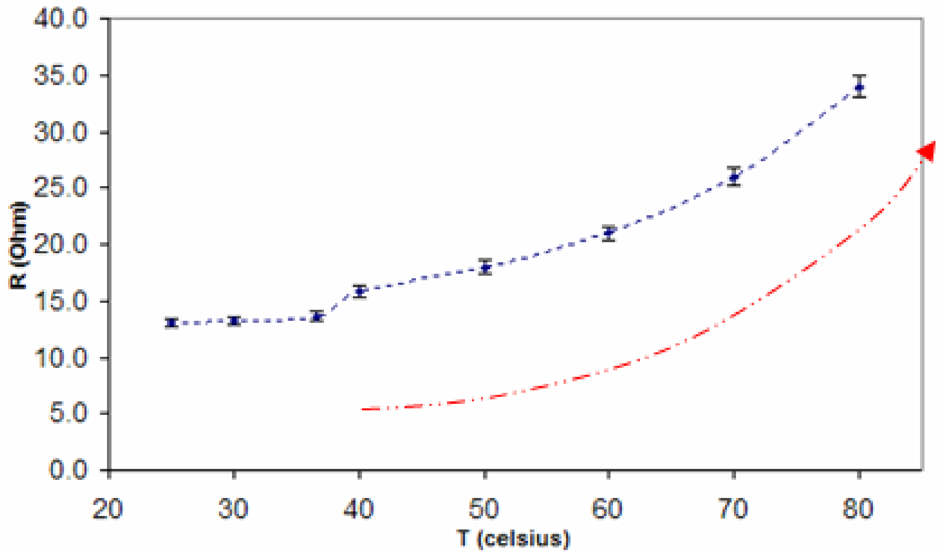

Fig. 6. Electrical Resistance changes over time held under constant applied load of 1000 g/cm^2 as a function of temperature T. The sample thickness is 0.5 mm with contact area of 1 cm^2. The conductive polymer transducer exhibits the electrical resistivity dependence as a function of temperature much like a weak semiconductor with a negative indirect energy band gap.

5. Conclusions

The conductive polymer based impact sensor approach has shown successful test results under standard laboratory condition. The governing state equation of the conductive polymer based transducer is as derived in equation (3). It is accurate in terms of both the sensor trends and functionality (negative exponential inclination). The transducer's resistance is also dependent on the surrounding thermal effects. This is an added advantage besides monitoring impact it can also double as an elevated thermal indicator, as most ammunitions are thermal sensitive too.

A shock and vibration test bench is build to test the fabricated impact sensors. An environmental chamber is used to test the conductive polymer transducer's thermal response in the cycling range of 25^{o}C to 80^{o}C. This result is reported as well. It is found that the conductive polymer transducer exhibits a very weak semiconductor-like temperature dependence of resistance.

The external applied load or pressure dependence of the conductive polymer transducer response is studied and reported. The observed conductive polymer transducer's resistance output, of 0.5 mm conductive polymer thickness as in Fig. 4, decays exponentially with external applied loads. Next, the loading time dependence of the conductive polymer transducer electrical resistance on constant pressure is investigated. The conductive polymer transducer electrical resistance response is found to be stabilized after about 6 sec.

The conductive polymer based impact sensor exhibit good resistivity characteristics with external applied force/pressure. The increase in conductivity or lower resistance observed, with the external applied pressure may be explained as a result of the formations of the conductive structure of the electro-conductive nano-size channel network. When a shock or impact is incident to the conductive polymer shock transducer, the resistance will be altered because of the change of the conductive particle separation.

Acknowledgements

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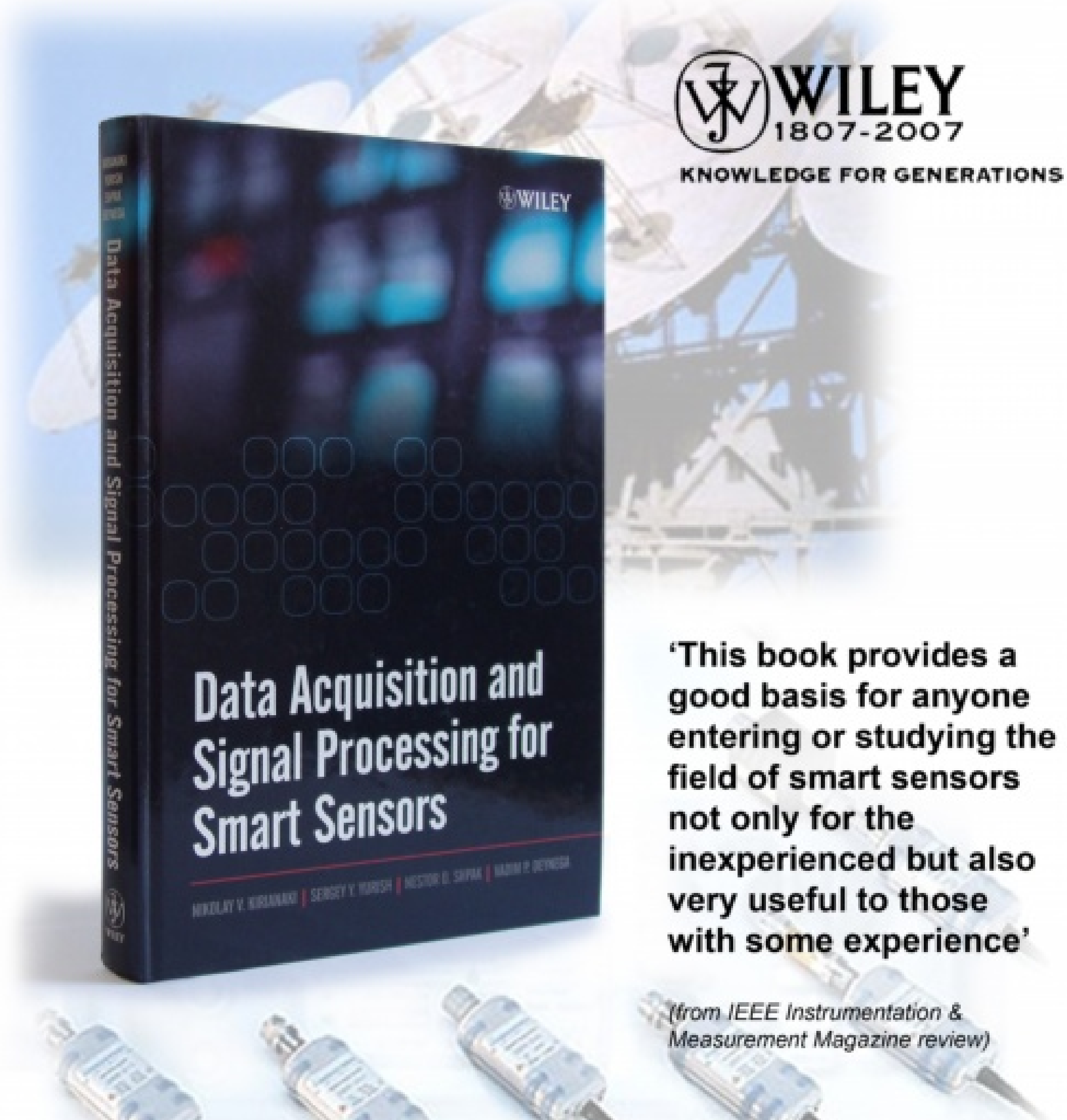

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