Distributed Piezoelectric Thin Film Sensor Array for Monitoring Impact Events

Sudeep Joshi[a], M.M. Nayak[b] and K. Rajanna[a]

[a]Department of Instrumentation and Applied Physics, Indian Institute of Science, Bangalore-560012, India
[b]Centre for Nano Science and Engineering, Indian Institute of Science, Bangalore-560012, India
E-mail: sudeepjoshila@gmail.com, mmnayak@gmail.com and kraj@isu.iisc.ernet.in

Abstract—Accurate monitoring of impact events is of paramount importance for structural health monitoring, quality control and failure analysis of numerous structures. The present paper reports on the application aspect of distributed piezoelectric Thin Film Sensor Array (TFSA) for the impact force measurement. The distributed TFSA consists of 3x3 sensing element matrix of piezoelectric ZnO thin film. Highly c-axis oriented piezoelectric ZnO thin film was deposited on the flexible Phynox alloy substrate by RF reactive magnetron sputtering and was characterized by FESEM and AFM techniques. The individual sensing element is a MIM (Metal Insulator Metal) type structure. The ZnO thin film acts as an impact sensing layer and is sandwiched between Phynox common electrode and silver thin film as a top electrode. The overall dimension of the developed TFSA was 3cm x 3cm, and it monitors the location, force-time history and magnitude of the impact force. The developed piezoelectric TFSA has potential applications in monitoring the impact events on several composite structures like wings of an aircraft, crash testing of vehicles and wearable sports impact indicators.

Keywords: Piezoelectricity; Impact sensing; ZnO thin film

I. INTRODUCTION

Various structures during their lifetime encounter several types of impact forces resulting in degradation of the performance and ultimately leading to their failure. Therefore, monitoring of impact events is of immense importance for the proper maintainability and assuring safety of structures. Presently existing literatures mainly reports on the impact force measurements from sensors array made of bulk piezoceramic materials [1-2]. These materials have a major disadvantage that they find it difficult to be integrated with the state of the art MEMS (Micro Electro Mechanical Systems) fabrication techniques. Additionally, these materials make the overall sensing system bulky. This has given us a motivation to put a step forward and integrate sensing thin film directly on the structure.

Zinc-Oxide (ZnO) is a promising II-VI group material, which possesses good piezoelectric and semiconducting properties. Owing to its good piezoelectric behavior in thin film form it has been used in many applications in sensors and actuators technology. A novel gas flow sensor [3], impact sensor [4] and micro actuator [5] have been reported. ZnO thin film has several advantages over its other counterparts, such as no need poling, which is required for PZT and PVDF films. It is compositionally simple material that can be deposited on large variety of substrates and it also possesses higher electromechanical coupling coefficient. The deposition of ZnO thin films on flexible substrates opens up new and exciting application possibilities in several areas.

In the present paper, highly c-axis oriented piezoelectric ZnO thin film was deposited on flexible Phynox substrate for the development of TFSA. The developed piezoelectric TFSA replaces the rigid multiple units of bulk piezoceramic sensors array with the single unit of multiple sensors, which is light weight and handy.

II. EXPERIMENTAL

A. *Fabrication of TFSA:*

Fig. 1 (a-b) shows the isometric and cross-sectional view of the fabricated TFSA, respectively. The distributed TFSA consists of 3x3 sensing element matrix of piezoelectric ZnO thin film. The piezoelectric ZnO thin film was deposited at optimized sputtering process parameters on the flexible Phynox substrate of dimension 3cm x 3cm. Phynox (Elgiloy) (Lamineries, MATTHEY SA) is an austenitic cobalt based alloy [6]. Phynox possesses exceptional spring properties, which make it a suitable material for the fabrication of sensing element. Suitable mechanical masks were designed for the deposition of ZnO sensing film, and also for silver thin film as a top electrode. The individual sensing element is an MIM structure. The ZnO thin film (thickness: 700 ± 30 nm) acts as an impact sensing layer and is sandwiched between Phynox common electrode (thickness: 40 µm) and silver thin film (thickness: 100 nm) as a top electrode. The active sensing area of individual sensing element (i.e. ZnO thin film deposited region) was 0.7cm x 0.7cm. The overall dimension of the developed TFSA was 3cm x 3cm and it monitors the location, force-time history and magnitude of the impact force. Fig. 2 shows the photograph of the fabricated TFSA.

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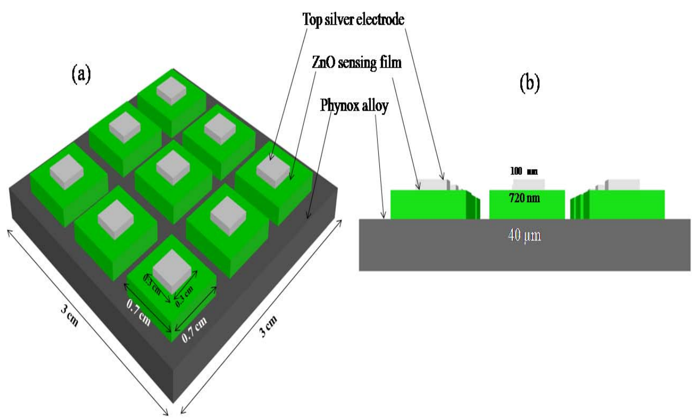

Figure 1(a-b): Isometric and cross-sectional view of the fabricated TFSA.

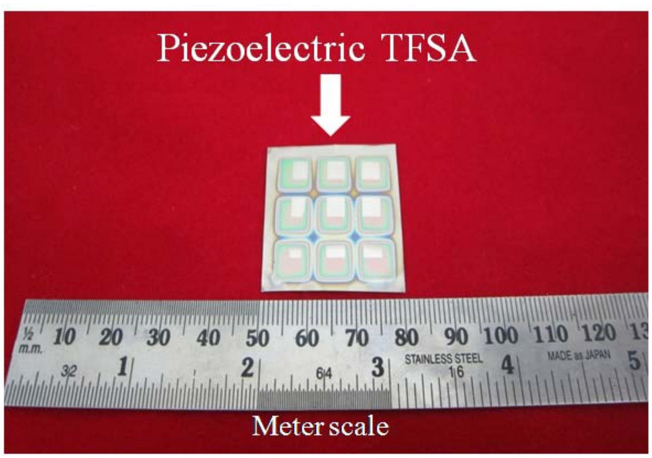

Figure 2: Photograph of the fabricated TFSA on flexible Phynox substrate.

B. *Impact detection scheme by employing TFSA:*

Fig. 3 shows the basic schematic of the impact detection scheme. The impact event at any location on the TFSA is sensed by the ZnO thin film sensing elements that are in the close vicinity of the impact force. As can be seen in the figure 3, the TFSA can be used for detecting the location, measurement of impact force magnitude and for estimating the force-time history of impact events. The schematic diagram of in-house designed experimental set-up employed for monitoring impact events is shown in fig. 4. It consists of a calibrated impact hammer (PCB, Piezotronics), developed TFSA and a digital storage oscilloscope (Tektronix). As there were 9 sensing elements on the TFSA so, individually they were connected to 9 channels of the CRO. The impact force of magnitude 8.2 mN was made with a calibrated impact hammer. This impact force causes the mechanical deformation of the deposited ZnO sensing film. The ZnO film is having non-centrosymmetric crystal structure as a result a piezoelectric potential difference is generated in between the two electrodes due to the stress induced piezoelectric effect. This developed potential difference is responsible for the flow of charges in between the two electrodes. The generated charges were then collected by electrodes and the output voltage waveforms were recorded in the oscilloscope.

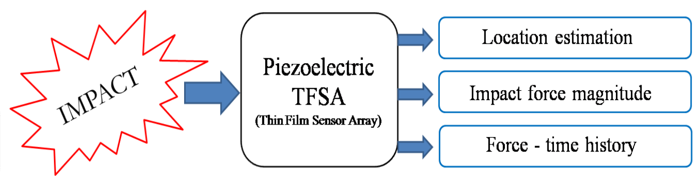

Figure 3: Basic schematic diagram of impact detection scheme from the fabricated TFSA.

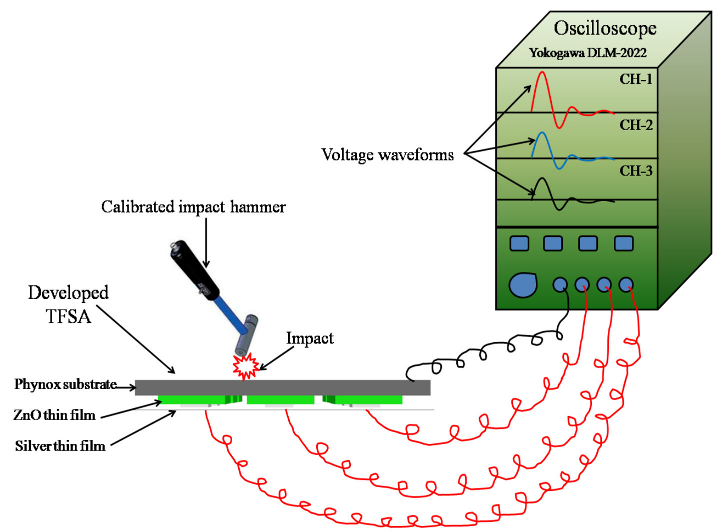

Figure 4: Schematic of the in-house designed experimental set-up for monitoring impact events.

III. RESULTS AND DISCUSSIONS

A. *Characterization of ZnO sensing film:*

Fig. 5 (a & b) shows the FESEM images (cross-sectional and top surface view) of the as-deposited ZnO thin film. As can be seen in the cross-sectional view, the as-deposited ZnO thin film possesses homogenous columnar structure perpendicular to the substrate surface. This is an indication of highly c-axis oriented piezoelectric thin film [7]. The measured thickness of the ZnO thin film was about 720 nm. The top surface view (*see fig. 5(b)*) reveals that the surface of the ZnO thin film was smooth, dense and free from defects. This is an indication of proper structural development of the as-deposited film at optimized sputtering process parameters. The film was having well oriented grains with uniform and large grain size in the range from 70-75 nm. Fig. 6 shows the 3D AFM image of the ZnO thin film for the measurement of rms surface roughness. Lower the surface roughness better is the piezoelectric property of the thin film. The measured rms surface roughness value of ZnO thin film was about 1.87 nm. Therefore, material characterization studies reveals that high quality ZnO thin film was obtained on the Phynox substrate at optimized sputtering process parameters.

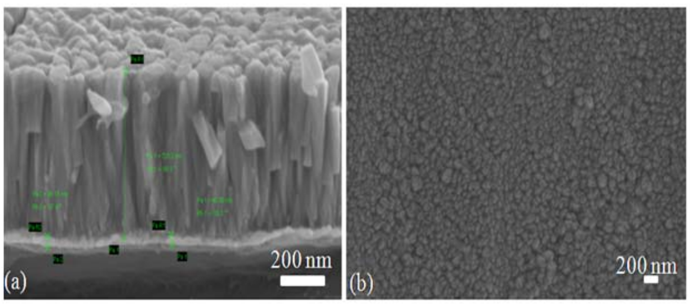

Figure 5(a-b): FESEM images of as-deposited ZnO thin film (a) cross-sectional view and (b) top surface view.

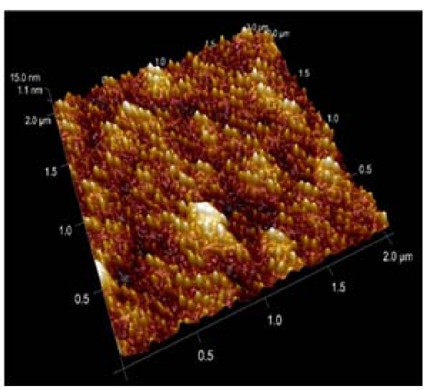

Figure 6: 3D AFM image showing rms surface roughness of as-deposited ZnO sensing film.

B. Analysis of generated output voltage from the TFSA:

Fig. 7 shows the location of impact made with a calibrated hammer on the TFSA and the corresponding output voltage signals generated from the sensing elements in the close vicinity. The impact force location was near to the 2nd sensor position (*see fig. 7 "red spot"*) therefore, it generates higher magnitude of the output voltage peak of 1.27 V. As the distance of the sensor position increases from the impact location, the magnitude of generated output voltage peaks decreases. The 3rd, 5th and 6th sensor generates relatively lesser magnitude voltage peaks of 0.82 V, 0.52 V and 0.45 V respectively. Therefore, the sensor in the close vicinity of the impact force generates highest peak output voltage and hence the TFSA locates the position of impact force.

Fig. 8 shows the output voltage magnitude at different sensor positions due to the same magnitude of impact force (8.2 mN) at various locations on the sensor array. As can be seen in the figure, the generated output voltages are of almost equal magnitude, as the impact force was same. Therefore, depending upon the magnitude of the generated output voltage peaks, the piezoelectric TFSA can be used to measure the magnitude of impact force. Moreover, fig. 8 clearly helps in locating the position of impact force based upon the height of the bar. The fig. 8 can help in the estimation of the force-time history of the impact event as well.

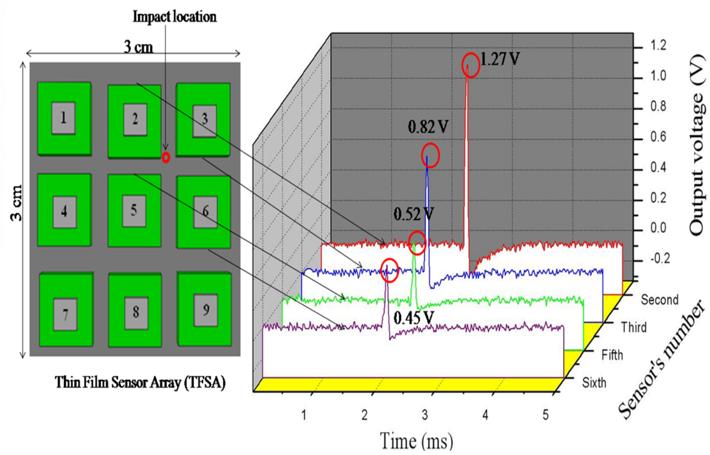

Figure 7: Location of impact force on the fabricated TFSA and corresponding output voltage signals generated from individual sensors.

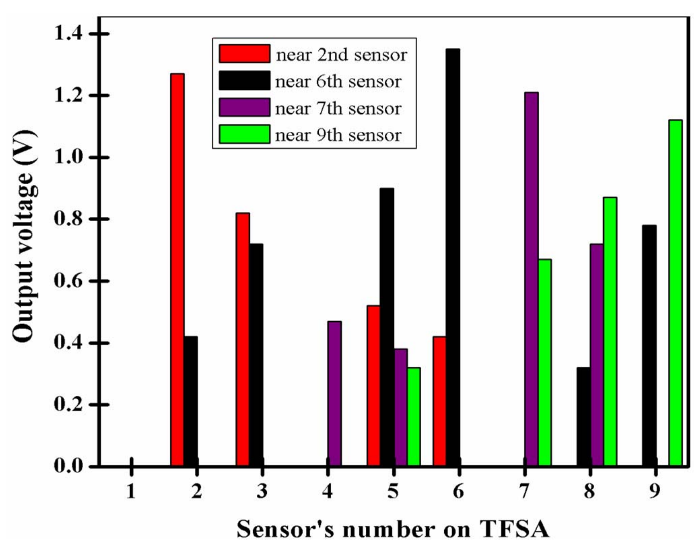

Figure 8: Output voltage responses from different sensor positions.

IV. CONCLUSION

The present experimental study discusses the successful development and application of TFSA. Arrays of optimized piezoelectric ZnO thin film as an impact sensing elements was deposited on the square Phynox substrate. The developed TFSA was then used in an experimental set-up for monitoring impact events. The TFSA was able to correctly identify the location and magnitude of the impact force at different positions on the sensor array. The developed TFSA has potential application possibilities in the following areas:

1. Wearable sports indicators.
2. Wings of an aircraft.
3. Clinical monitoring of head impacts.

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