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Scalable Platform for Batch Fabrication of Micro/Nano Devices on Engineering Substrates of Arbitrary Shapes and Sizes

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Abstract
Silicon wafers with standard sizes and shapes have served as the batch fabrication platform for microfabrication of micro/nano devices for decades. However, there is a strong demand to batch fabricate micro/nano devices on other engineering materials (e.g. titanium, stainless steel, diamond, and ceramics) of complicate shapes and sizes designed for important applications. Unfortunately it is extremely difficult to meet the demand due to various challenges involved during microfabrication. Here we present a novel batch fabrication platform which can be used to facilitate the batch fabrication of thin film devices on substrates with arbitrary shapes and sizes. This platform will eliminate photolithography related defects such as edge bead formation, which will enable fabrication of thin film devices at the edges/corners of arbitrary shaped and sized substrates. At the same time it will enable uniform and bulk polishing of these substrates. As a proof of concept, parallel/batch fabrication process was successfully applied and proved by fabricating thin film piezoelectric force sensors on polygonal shaped stainless steel plates.

Keywords: Batch fabrication, Microfabrication, Thin film sensors

1 Introduction

In numerous engineering processes, such as manufacturing, the ability to measure temperatures, stresses, cutting forces, etc. is not only crucial for monitoring the machine tools but also for reliable real-time process control (Zheng, 1993, Totis, 2011, Ma, 2011, Siddhpura, 2013). Micro/nano sensors and devices present a promising way to advance process monitoring and control. However, in the industrial processes, such as manufacturing, there are

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tremendous challenges for the adaption of micro/nano sensor and devices, such as substrate's geometric
constraints, material compatibility, and harsh operation conditions (Siddhpura, 2013). Recent years have seen a rigorous development of such sensing techniques, where micro/nano sensors are fabricated on engineering materials, such as PCBN cutting tools, sapphire, and stainless steel etc. (Datta, 2006, Li., 2013, Werschmoeller, 2009, Zhang, 2006, Choi, 2007). There is a strong demand to batch fabricate micro/nano devices on other engineering materials (e.g. titanium, stainless steel, diamond, and ceramics). Unfortunately it is extremely difficult to meet the demand of batch fabrication due to the substrates needed for engineering applications normally are in complicate shapes and sizes. Unlike conventional silicon wafer based platform for batch fabrication, wafers of other engineering materials with satisfactory surface quality are extremely difficult to obtain, sometimes impossible due to manufacturing limitations. Moreover, techniques involving fabricating devices on large wafers of metals and ceramics, and later use laser or diamond saw dicing to obtain devices of suitable sizes and shapes would create problems due to the harsh conditions in these processes, which easily induce cracks and residual stresses. Some more challenges are discussed below.

1.1 Bulk Surface Polishing And Fabrication

The substrates such as PCBN, sapphire, stainless steel and other potential substrates have to undergo surface polishing process before thin film devices can be fabricated on them. Individual polishing and fabrication of these devices is a very time consuming process. These issues become more time consuming and cost ineffective when large scale production of such devices are in demand. In order to achieve high throughput, an efficient batch fabrication process is needed. The approach of parallelized or batch fabrication in microelectronics often leads to high yield, cost reduction and improved miniaturization. In order to keep pace with competition, the industries have to achieve short production time and high throughput under lowest investment (Tu, 2011).

1.2 Geometry Affected Photolithography Challenges: Edge Bead Effects

In addition to the need of batch fabrication of these miniaturized devices, there is another challenge of overcoming geometric constraints i.e. to fabricate the sensing devices at the edge / perimeter of the small substrates for better sensing spatial and temporal resolution (Li, 2013, Werschmoeller, 2009). During the photolithography process, the spin coating of photoresist and other such polymers/chemicals often results in planarization defects such as edge bead formation (Carlson, 2007, Chaplick, 2010, Elliott, 2012, Ishida, 1996, Jekauc, 2004, Lee, 2011, Oberlander, 2001, Rekhson, 1991) on the substrates as shown in Figure 1. The edge bead formation depends on various factors

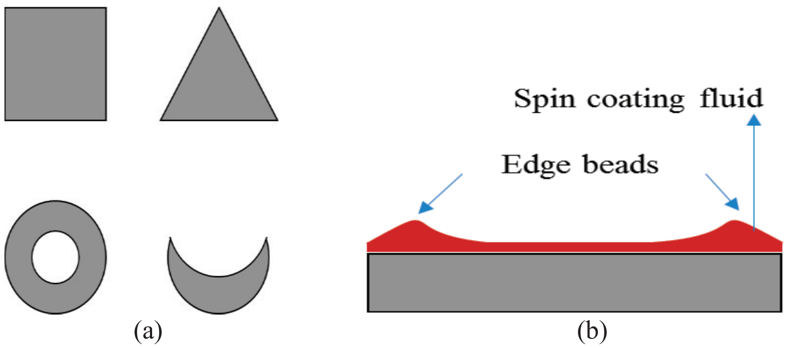


Figure 1: AlN force sensor consisting of top and bottom electrodes sandwiching a piezoelectric AlN thin film disc.

such as the viscosity of the spinning fluid, rate of spinning, and time (Lee, 2011, Middleman, 1987, Uddin, 2004).

Moreover, these edge beads forms a tiny air gap between the mask and the substrate during UV exposure resulting in diffraction of light leading to inaccurate patterning (Lee, 2011, Chuang, 2002). Present methodology involved to eliminate these edge bead effects include either makeshift methods like gentle application of razor blade or clean room swab while the substrate is spinning or expensive edge bead removal fluids such as EBR (EBR-PG from Micro-Chem Corp., newton, MA, USA)[16, 22, 23]. Other standard techniques include, advanced spinner machine capable of applying a stream of EBR at the edge of the wafer through a nozzle while spinning or wafer-edge exposure system where the wafer edge is exposed to a broad band exposure thereby reducing the edge bead buildup (Jekauc, 2004, Lee, 2011). However, these techniques always affect the edges and reduce significant usable area. It is also observed that events such as solvent splashing leads to quantifiable amount of yield loss (Jekauc, 2004). Furthermore, these methods cannot be applied to tiny substrates/dies of the order of a few milli- /centimeters and to substrates with sharp edges such as rectangle, triangle, arc and other polygonal shapes (Lee, 2011).

To address all the issues discussed above, we attempted to develop a process technique which could overcome these hurdles. The new process is to make epoxy mount wafers that contains the substrates of metals, ceramics and other materials in complicated geometry and small sizes. The epoxy wafers will serve as a new platform to enable a batch fabrication of micro/nano sensors and devices on these substrates. This process is compatible with conventional thin film deposition and most of the wet processes. Furthermore, our technique can be easily scaled to larger dimensions.

2 EXPERIMENTAL

2.1 Batch Mounting Of Metal Plates

The schematic of the new batch fabrication process based on a scalable platform is shown in Figure 2. A two sided transparent tape was placed on a plastic transparency sheet. The transparency sheet with the tape on its top was then rested on a glass mask. The stainless steel plates with square and arbitrary polygonal structure were accurately placed to the two sided tape, following the mask pattern as an alignment tool. The main reason to use stainless steel material as a substrate in this paper instead of any other material (say Silicon) is due to its high hardness and ability to withstand strong forces > 200N. Moreover, stainless steel is readily available in thin sheets and can be cut into desired arbitrary shapes.

The dimensions on the mask pattern was set to be similar to the dimensions of the substrate. The misalignment was minimized with the aid of a light source at the bottom of the mask and a magnifying glass while placing the steel substrates. For most applications this alignment approach is quite reliable. For substrates requiring more precise placement, a custom made computer controlled robotic arm like device with a combination of microscopic lens could be used. A circular plastic frame with a radius of 3" was used to hold a mixture of epoxy mount resin and hardener (Allied High Tech) in a 10:3 ratio. The entire steel plates, except the top face (for sensor fabrication), were covered by the epoxy mixture. After curing at 40 °C for about 2 hours, a hard epoxy disc with the steel plates embedded on its surface is obtained. The epoxy disc is then polished on both back and front side using lapping technique. This reduces the overall thickness and surface roughness of the epoxy disc, giving it an epoxy wafer appearance.

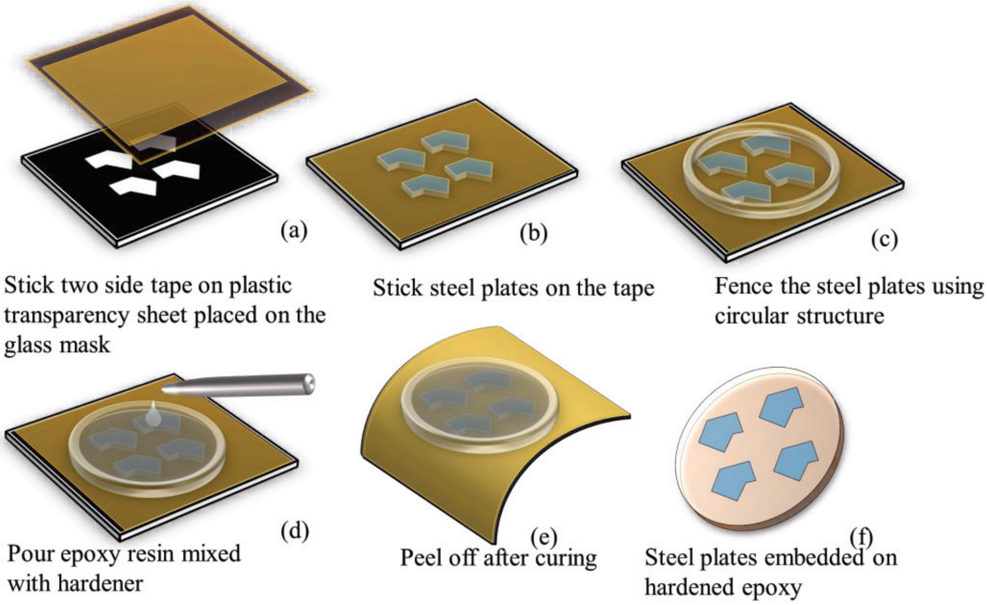


Figure 2: A new scalable platform for batch fabrication, (a) Two sided tape pasted on a thin plastic transparency sheet placed on the glass mask, (b) steel plates placed onto the two sided tape, hence holding them fixed, (c) circular frame is placed on the tape, (d) a mixture of epoxy mount resin and hardener (10:3) poured into the circular fence and cured at 40 °C for 2 hours, (e) Hardened epoxy disc peeled off from the plastic sheet, (f) Hardened epoxy disc with steel plates embedded on its surface.

2.2 Batch Polishing

For thin films deposition and patterning for microfabrication, it is necessary to have a flat surface and adequate roughness. A rugged surface might result in complications like pinholes, random or off

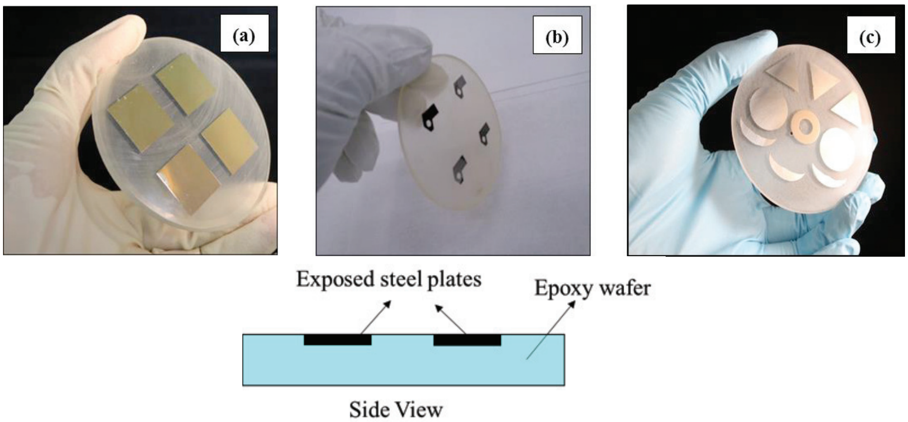
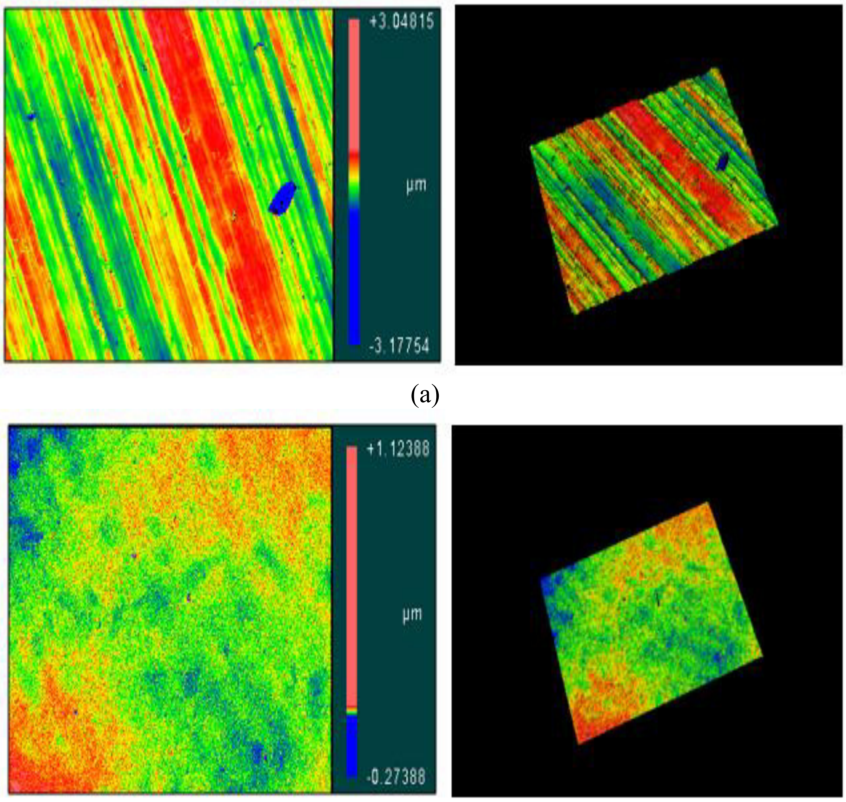


Figure 3: Epoxy wafers containing steel substrates (a) Square, (b) Arbitrary shaped embedded stainless steel plates on the epoxy wafer surface, (c) schematic of the side view of top surface exposed steel plates

c-axis orientation of the thin film due to the disordering of the nucleation site (Artieda, 2009). The steel plates embedded on epoxy disc were batch grinded and polished to reduce the surface roughness and to obtain an overall flat surface for photolithography and metal deposition, as shown in Figure3. The plate samples embedded epoxy wafers were polished using diamond suspension solution or slurry with particle size 1 µm, 0.1 µm and 0.05 µm and was later ultrasonically cleaned with acetone, IPA and DI water to remove contamination and residuals.

The average surface roughness of the steel plates were determined to be about 0.223 µm using Zygo white light interferometer before polishing, and about 0.005 µm after polishing. Figure 4 shows the average surface roughness of the polished steel plate before and after polishing. This demonstrates that this process can be utilized to mass polish specimens, hence avoiding time consuming one-by-one polishing.



(a)

(b)

Figure 4: Surface roughness of steel plate, (a) before polishing, (b) after polishing

2.3 Batch Fabrication Of Micro Sensors

It should be noted that the fabrication method described here is applicable not only for stainless steel but for any other metallic or nonmetallic (e.g., ceramic) material system. The final product of the batch fabricated devices on steel plates is shown in Figure 5. The steel plates can be readily taken out using a sharp edged stylus while the epoxy wafer is on hot plate at ~ 300 °C.

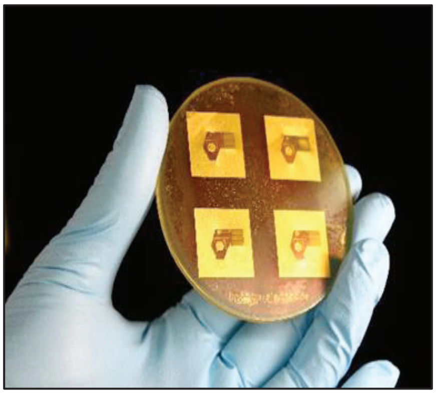


Figure 5: AlN thin film force sensors batch fabricated on stainless steel plates in an epoxy wafer

The batch sensor fabrication involves multiple process steps: (a) Polishing of the stainless steel plates embedded on the epoxy disk (as shown in Fig. 3(b)), (b) deposition of a stack of insulation layer on the steel plates using e-beam evaporation followed by alumina deposition using atomic layer deposition (ALD) and another layer of alumina using e-beam evaporation. This process of multiple layer alumina deposition ensures a pinhole free insulation layer; (c) deposition of Ti/Au for the bottom electrode; (d) deposition of the AlN piezoelectric layer; (e) deposition of Ti/Au for the top electrode, (f) finally, a protective coating of Aluminum Oxynitride (AlON) was deposited to encapsulate the entire sensor and, thereby, protecting it from scratches and other wear/tear influences. The fabrication process flow is illustrated in Figure 6.

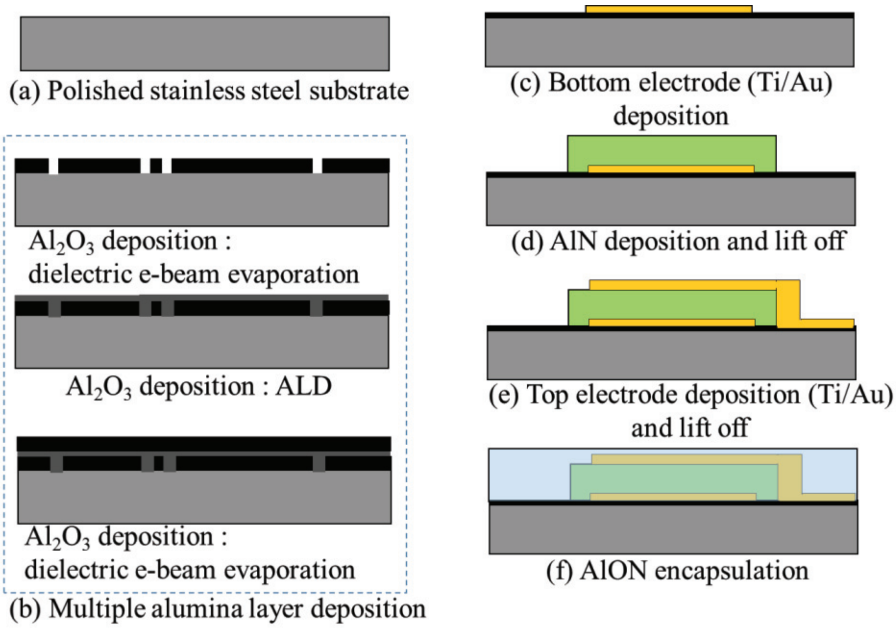


Figure 6: The batch fabrication process of sensors on stainless steel plates

The epoxy resin and hardener mix used here has been proved to be very compatible for low temperature (less than 300 °C) processing such as sputtering, e-beam metal/dielectric deposition. The surface of the epoxy resin was microscopically inspected to determine any surface modification signs during metal deposition and wet chemically processing such as wafer cleaning (using IPA, Acetone, DI water), photolithography (using LOR-3A, Shipley 1813, MF321) and liftoff (using acetone). No visual signs of chemical reactions / surface modification were ever witnessed, which proves its compatibility and reliability with the above mentioned processing tools and chemicals. Its compatibility with other processing chemicals is not yet completely known. Further research /testing is required to prove the reliability of this epoxy mixture to other chemicals and processes. As most of the lithography and patterning were done chemically, no lethal residual signs were shown on the substrates when inspected under microscope.

2.4 Wire Bond Encapsulation

During data acquisition from the sensor, it is difficult to draw the electrical wires from the sensor's compact electrode pads using conventional lead connection techniques like soldering, silver paste, electrode clips, etc. This is because the sensor pads are too tiny and very close to each other. The use of solder or silver paste would result in short circuit with neighboring electrode pads or the bottom substrates.

To avoid the above-described problems, we used the approach of using wire bonding techniques to connect the sensor electrode pads with external circuit boards and encapsulating the delicate wire bonds with a mixture of epoxy mount resin and hardener in a 10:3 ratio. The epoxy mount mixture was poured in small quantity over the wire bonding area and was cured at room temperature, thus, creating a hard epoxy encapsulation which provides protection for the fragile wire bonds from external wear and tear during the various manufacturing processes. Figure 7 (a-c) shows a conceptual view of the epoxy encapsulated wire bonding technique and (d) gives the real time image of the hard epoxy encapsulated wire bonding technique.

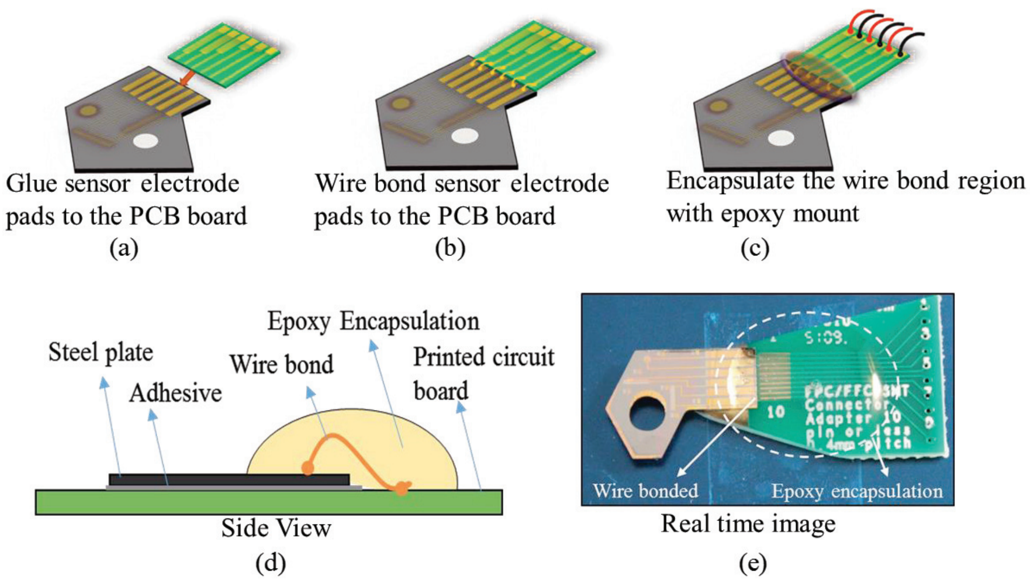


Figure 7: AlN thin film force sensors batch fabricated on stainless steel plates in an epoxy wafer

3 RESULTS AND DISCUSSION

3.1 Sensor Quasistatic Calibration

The sensitivity of AlN piezoelectric sensor fabricated at the edge of the steel plate as shown in Figure 8(a) was characterized to obtain the charge-to-force coefficient (pC/N) in the longitudinal direction, i.e. piezoelectric coefficient (d_{33}). The resulting d_{33} value was multiplied by the ratio of area of load cell attached pressure head (circular) and area of sensor (circular) to obtain the effective piezoelectric coefficient along the longitudinal direction, i.e. d_{33eff}, which is ~3.15 pC/N. The quasistatic calibration of the sensor was performed using a servo hydraulic material testing system (MTS load frame). It is equipped with a pressure head connected to a load cell acting as a reference force sensor. A load was applied on the AlN sensor (connect to charge amplifier) using the loading shaft of the MTS system and resultant output voltage was corresponded to charge using the Kistler 5004 charge amplifier. NI 6070E functions as a data acquisition systems with LabVIEW software to

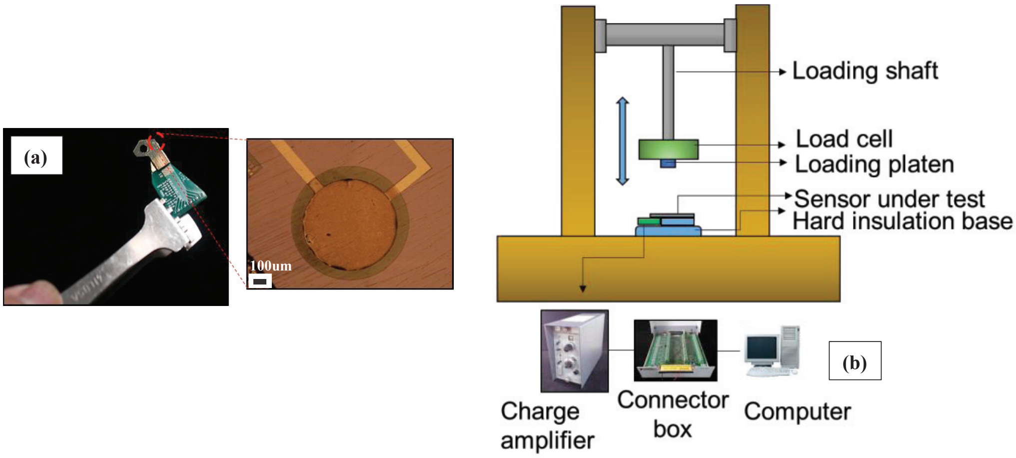


Figure 8: (a) AlN piezoelectric force sensor fabricated at the edge of the steel plate, (b) A schematic of

acquire, process, and log the data.

The initial load applied on the transducer was 25 N, then was increased to 225 N in a step increment of 25 N. The linear calibration curve obtained from the compression load and sensor output (average of three trials) are shown in Figure 9.

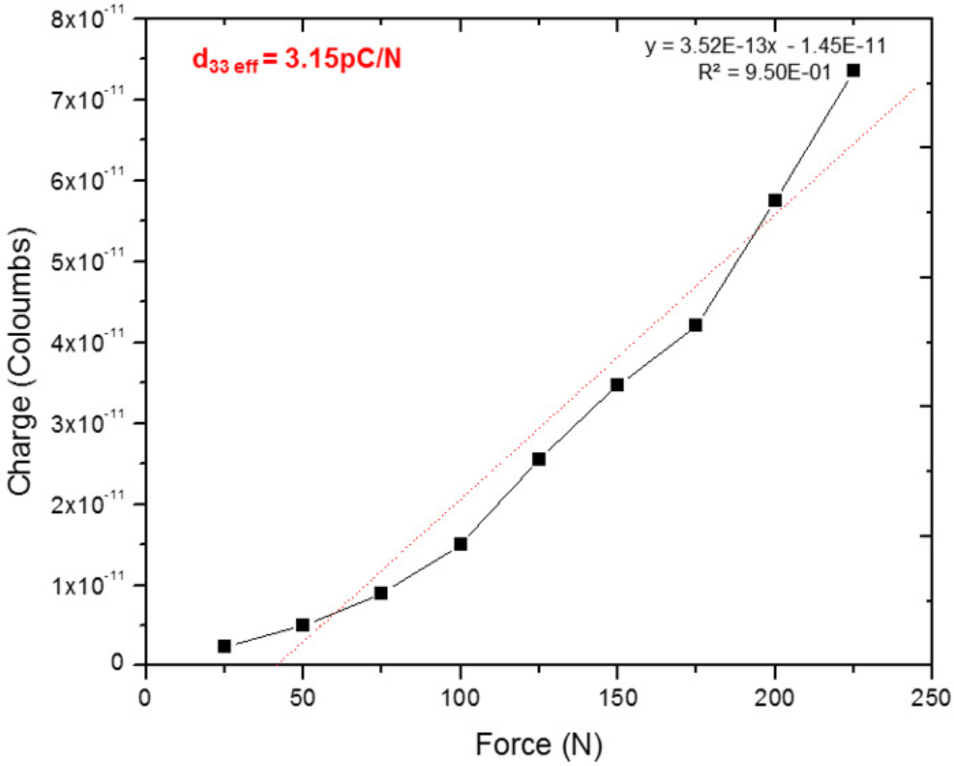


Figure 9: Force response of AlN thin film sensors obtained through quasistatic characterization

4 CONCLUSION

A novel scalable platform has been developed for a batch fabrication of thin film devices on substrates of engineering materials (such as metals, ceramics and others) in arbitrary shapes and sizes. This platform effectively eliminates photolithography related defects such as edge bead formation, enabling a batch fabrication of thin film devices at the edges/corners of arbitrary shaped and sized substrates for important engineering applications. Parallel/batch fabrication process was successfully demonstrated to fabricate thin film piezoelectric force sensors on polygonal shaped stainless steel plates. This novel batch fabrication can improve the yield by allowing more substrates to be fabricated at a given time. This can also significantly reduce the production time and cost thereby making large scale fabrication and application feasible. An epoxy encapsulated wire bond approach was used to integrate these miniature devices with compact electrode pads to data acquisition systems. This process is also applicable for other possible substrates such as diamonds inserts, WC inserts, PCBN inserts and other tiny structures with arbitrary shapes.

5 ACKNOWLEDGMENTS

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6 NOMENCLATURE

Symbols

d_{33}	Piezoelectric coefficient along longitudinal direction	pC/N
d_{33eff}	Effective piezoelectric coefficient	pC/N

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