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Microelectromechnical System Pressure Sensor for Projectile Applications

by Eugene Zakar

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Microelectromechanical System Pressure Sensor for Projectile Applications

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14. ABSTRACT
A miniaturized high pressure sensor for cannon-launched munitions was fabricated, based on microelectromechanical system (MEMS) technology. It uses a 0.5-µm thin film of lead zirconate titanate (PZT) material for producing an electrical charge that is directly proportional to the pressure. The sensor was mounted on a customized stainless steel housing, placed into a high-pressure vessel, and tested to a maximum pressure of 40,000 psi. The shape and configuration of the platinum (Pt)/PZT/Pt layered structure has been redesigned to reduce the complexity of wire interconnections and to increase the charge output of the device.

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Sensor, pressure, PZT, sol-gel-piezoelectric, MEMS

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1. Introduction

The ultimate trajectory and accuracy of a projectile launched from a large caliber cannon depend on several factors, including the cannon's base pressure. This parameter has not been measured directly to date. The ability to measure in-bore disturbances directly and predict launch conditions would accelerate the development of "smart" projectiles. Existing techniques for determining base pressure include copper crush washer gauges mixed with explosive and quartz pressure gauges mounted externally through penetrations along the walls of the cannon. The copper washer measures only the peak pressure generated by the explosive. The quartz gauges measure the breech pressure but not the base pressure. The current indirect method of determining the base pressure estimates the pressure from the data collected from the various gauges. There remains a critical need to develop a pressure sensor capable of directly measuring in-bore pressures in order to assist in the test and evaluation of more and more sophisticated projectiles being developed.

One of the main problems facing the instrumentation of a projectile is physical space. This is especially challenging for a 120-mm diameter tank kinetic energy (KE) projectile consisting of a long, solid rod with a pointed windshield and a small set of fins for stabilization. With the exception of the tracer well cavity in the tail end, there is no space for an instrumentation package. Any modifications of the projectile can create adverse effects to the trajectory and are therefore prohibited.

Similar space confinement issues have occurred with spin rate instruments. Spin rates have been measured for free flight projectiles (*1*) at the U.S. Army Research Laboratory (ARL) with an optically based yawsonde that measures angles with respect to the sun (*2*) or a magnetometer sensor that uses a bridge circuit comprised of giant magnetoresitive elements (*3*). Each of the latter instruments was miniaturized to fit into a tracer well and comprised of both the sensor and a transmitter. This technique of miniaturization is ideal for free flight projectiles and is a possible approach to measuring the in-bore pressure at launch.

Conventional pressure sensors rely on capacitive sensing of the distortion of a diaphragm. However, during the launch of a projectile, the extreme distortion or displacement causes recovery times that are too long (often on the order of seconds) to be useful. One existing device for measuring pressure uses a tourmaline crystal transducer that has a linear capacitance change with pressure. A possible means of miniaturizing the pressure sensor as well as improving device characteristics is to use a piezoelectric thin film in place of the tourmaline crystal. With this device, the applied pressure will result in a material deformation generating a surface charge through the direct piezoelectric effect. Additionally, the use of micro-fabrication techniques will allow for batch processing of large numbers of sensors at one time.

Recently, there have been many research efforts in the use of lead zirconate titanate (PZT) thin films for various sensors and actuator applications (*4*, *5*). PZT thin films are very attractive because of their larger piezoelectric properties compared to more conventional piezoelectric materials such as zinc oxide (ZnO) and aluminum nitride (AlN). This research illustrates a novel approach at the fabrication of a PZT-based thin film pressure sensor and its subsequent performance at large pressures.

ARL's Sensor and Electron Devices Directorate is providing smart and intelligent sensors and radio frequency (RF) devices to Department of Defense (DoD) services to meet the requirement of Future Combat Systems (FCS). ARL is highly dedicated to support microelectormechanical system (MEMS) process and fabrication efforts for novel devices. The MEMS lab is specially equipped with advanced process and fabrication equipment for deposition, patterning (submicron), dry etching (submicron), and characterization of semiconductors and ceramic oxides (specifically dedicated to PZT). The MEMS lab has developed unique processes and fabricated submicron size features on silicon, PZT, and platinum (Pt) films.

2. Experiment

2.1 Preparation

The basic fabrication requires the preparation and deposition of a Pt/PZT/Pt sandwich structure surrounded by silicon dioxide (SiO_2) isolation film on a silicon substrate. Electrical contacts are made through holes etched in the SiO_2 layer to reach the bottom and top Pt electrodes via gold deposition. The two most critical steps are the deposition of the bottom Pt electrode and the PZT deposition.

2.2 Bottom Pt electrode

The ability to achieve proper crystallization of the piezoelectric PZT film is critical and is aided by the use of a Pt nucleation electrode formed by sputter deposition before the PZT deposition. The bottom Pt must have a microstructure with columnar grains and highly oriented in the (111) material crystal lattice direction. The sputtering conditions needed to accurately produce these films have been characterized and are summarized in table 1. Three steps are performed without the breaking of chamber vacuum pressure (in situ): (a) cleaning of the underlying SiO_2 surface with Argon etch, (b) deposition of tantalum (Ta) (20-nm adhesion layer), and (c) deposition of Pt (170 nm bottom electrode layer) at 100 ºC. The Pt is then annealed in a rapid thermal processor for 60 s at 700 ºC in nitrogen with an AG[1] Associates Heatpulse 410 system. In order to achieve the needed film qualities, we specifically selected a commercially available Varian 3190 sputter deposition system because of its unique features. The desirable sputtering features are close

[1] not an acronym.

source-to-substrate spacing (2.75 inches) for reduced gas inclusion and high film purity, conical shaped magnetron sputtering source for superior step coverage and film thickness uniformity, high efficiency gas conduction back side wafer heating for controlled film morphology, and vacuum load-lock chamber for reducing film contamination.

Table 1. Sputter conditions for bottom Pt electrodes.

	Step-1	**Step-2**	**Step-3**
Operation	Etch	Deposit	Deposit
Method	Argon sputter	Tantalum	Platinum
Temp.	Ambient	100 °C	100 °C
Pressure	13 mT	13 mT	7.5 mT
Power	1.3 Kv RF bias	1.2 Kw DC	1.0 Kw DC
Rate	33 nm/sec	160 nm/min	240 nm/min
Thickness	500 nm	20 nm	170 nm

2.3 PZT film

The PZT technology was established as a Defense Advanced Research Projects Agency (DARPA)-funded collaborative effort with ARL and Pennsylvania State University to develop procedures for the sol-gel deposition of crack-free PZT thin films as thick as 2 µm and with deposition temperatures compatible with pre-metallization back-end complementary metal oxide semiconductor (CMOS) processing. ARL has fully developed the process is now the only DoD facility that produces high quality sol-gel PZT for distribution to industry, academia, and other Government agencies. A complete description and procedure for the synthesis and preparation of sol-gel solution of PZT have been reported (*6*).

Transmission electron microscopy (TEM) was used to characterize and verify the film morphology shown in figure 1. The average size of the Pt grains is 180 nm; they are columnar in shape and highly oriented in the (111) direction as required. The PZT grains near the bottom Pt are equiaxed and evolve toward a columnar shape.

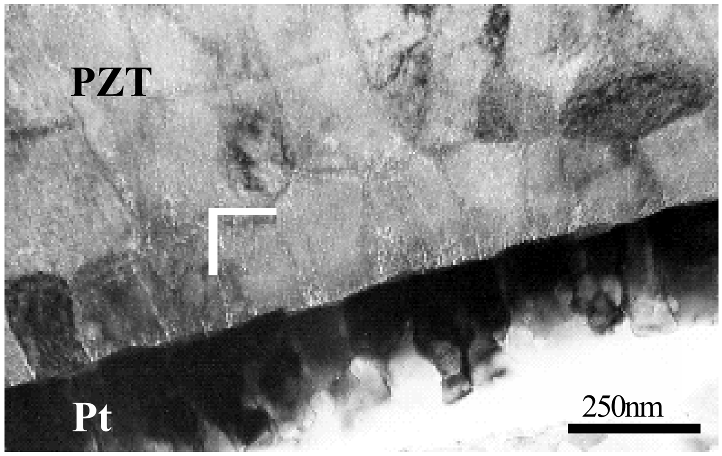
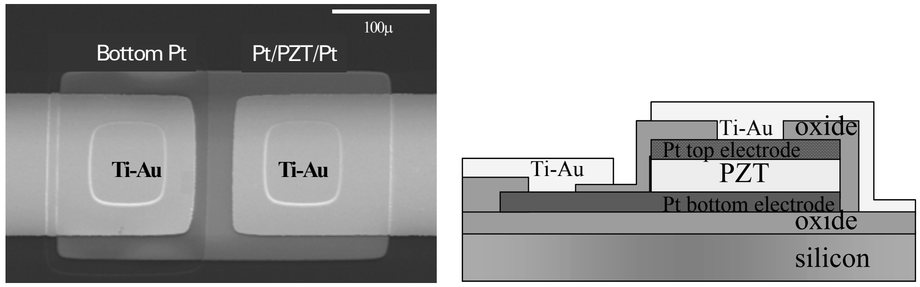


Figure 1. TEM image of Pt and PZT grain morphology.

2.4 Patterning and fabrication

After deposition of SiO_2/Ta/Pt/PZT/Pt on a silicon wafer, the fabrication process requires only four mask levels to define the structures. Etch level requires a photolithography masking step followed by an etching step. The first level defines and isolates the Pt/PZT/Pt island structure by ion beam etching process. The second level is used to expose the bottom Pt layer by ion beam etching of the top Pt followed by a highly selective etching of the PZT layer. A reactive ion etch (RIE) process that uses sulfur hexafluoride (SF_6) plasma chemistry (*7*) has been developed, which is highly selective and will only etch PZT film but stop when the bottom Pt electrode is finally exposed. After deposition of a top layer SiO_2 isolation film, the third level mask is used to make openings and expose the Pt contact areas with RIE. The fourth and last mask defines the gold output leads for the contact areas.

Processes, patterning details, and testing of capacitor structures suitable for the pressure sensor have also been reported (*8*). The plan view photograph and cross-sectional drawing of a fabricated device structure are depicted in figure 2a and 2b, respectively. The active sensor Pt/PZT/Pt capacitor surface area measures approximately 200 μm by 200 μm. This design was meant for process development and proof of concept.



(a) **(b)**

Figure 2. Fabricated device structure depicting (a) plan view and (b) cross-sectional drawing.

The challenge was to mount this PZT thin film capacitor device on a base that is suitable for high pressure testing. The base design of a commercially available tourmaline transducer routinely used for high-pressure measurement applications was considered. The fabrication of the base and the steps leading to the mounting of the PZT devices are described in figure 3. In order to increase the total electrical charge output of the pressure sensor, two PZT devices were mounted on the base and electrically connected in parallel by gold leads. A retainer cap with non-conducting epoxy was bonded over the base. The cap was then secured to a stem (not shown) and finally mounted into a customized stainless steel housing, as illustrated in figure 4. The PZT pressure sensor was tested at each of the following pressures: 10,000, 20,000, and 40,000 psi. The electrical charge output of the PZT sensor was measured and compared to a calibrated tourmaline sensor.

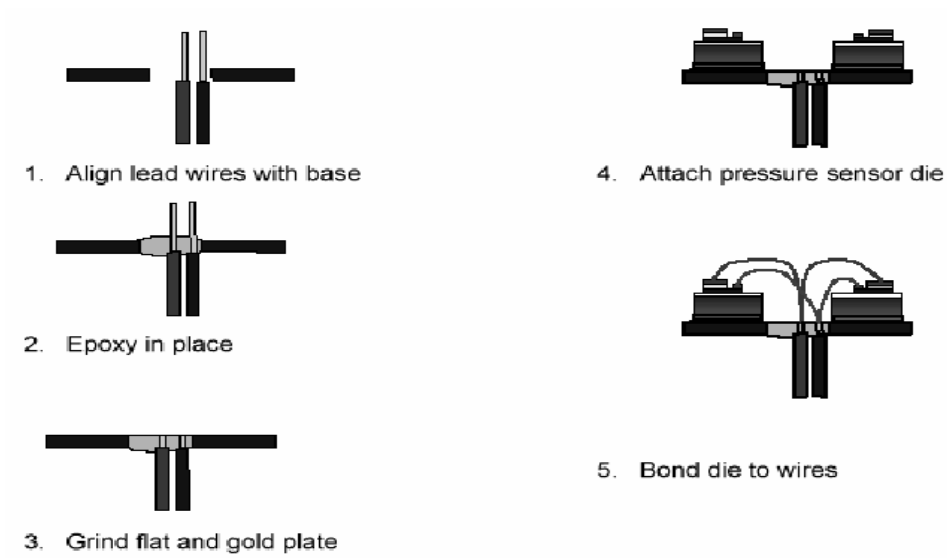


Figure 3. Fabrication steps of the base leading to the mounting and wire bonding of the PZT devices.

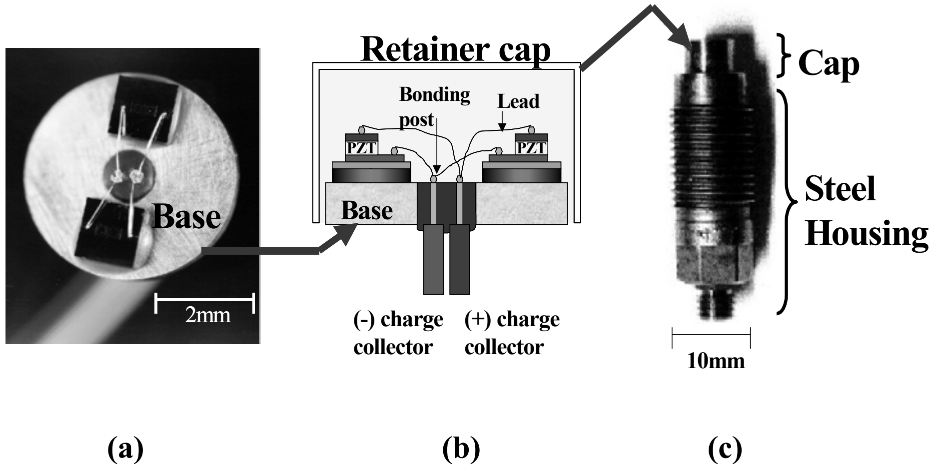


Figure 4. Stages of assembling the PZT device. (Photo of the base with (a) two PZT devices attached, (b) diagram representation of a retainer cap filled with epoxy and bonded to the base, and (c) photo of a completely encapsulated PZT sensor in a steel housing.)

3. Results

The measured output charge of the PZT pressure sensor was very low (approximately 60 times less), compared to the standard calibrated sensor. The large deviation between the sensors was expected because the physical dimensions of the two combined PZT devices were much smaller. The measured electrical charge response for the PZT sensor shown in figure 5 appeared proportional to the calibrated sensor for the 10,000-psi and 20,000-psi pressure ranges. The measured charge output increased from 77 pico coulomb (pC) to 130 pC for the PZT sensor while the calibrated sensor changed from 3,170 pC to 6,338 pC. However, at 40,000 psi, the PZT sensor charge output did not perform nearly as well as the calibrated sensor. The measured charge output increased from 130 pC to 202 pC for the PZT sensor and from 6,338 pC to 12,745 pC for the calibrated sensor. The charge doubled in value for the calibrated sensor but not nearly as much for the PZT sensor. The test was conducted two more times for both the sensors. The change for the PZT sensor continually decreased each time, whereas for the calibrated sensor remained the same.

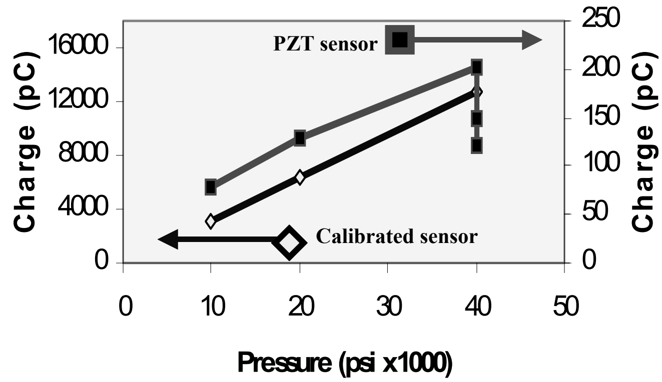


Figure 5. Measured electrical charge response for the PZT and calibrated sensors.

The abnormal behavior of the PZT sensor at 40,000 psi may be related to mounting and packaging issues. The use of multiple leads for electrical connections and their arrangements is also suspected. Changes in the degree of deformation and recovery of the bonded epoxy during repeated testing at the maximum pressure proved the inadequacy of this sensor design.

In order to improve the pressure sensing response of the original PZT design structure, we identified several areas that needed improvements. The multiple lead connections from the top side of the device were eliminated. To facilitate this, the PZT device was converted to a disc shape with an opening in the center similar in design to the calibrated sensor. Only one (+) output lead is connected to the top Pt charge collector, and only one (-) output lead connection is needed to the base, as shown in figure 6. Electrical contact to the flat shaped top charge collector plate is made through a micromachined opening in the PZT/Pt/Ta/SiO_2/silicon sandwich layers. The negative charge collector acts as both a base and common ground. However, because of the requirement of an insulating SiO_2 film that must remain between the bottom Pt and silicon surface, a modification before the deposition of the bottom Pt metallization is required. Via holes are etched through the very thin layer of SiO_2 to the silicon before the Pt electrode is sputter deposited and annealed. This modification allows electrical conduction between bottom Pt electrode and silicon base. The surface area of the PZT structure will also be enlarged to produce a higher charge output in response to an applied pressure.

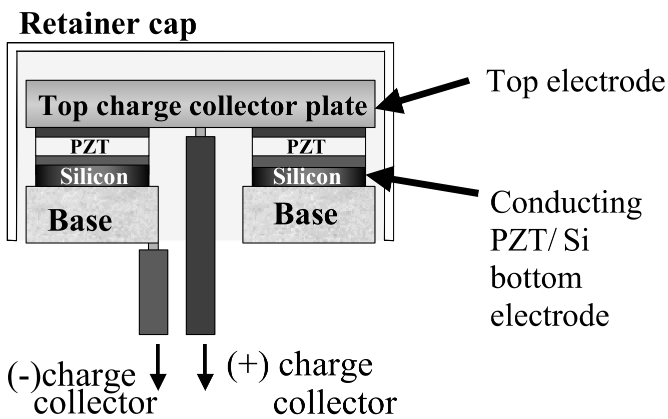


Figure 6. Drawing of new features for the next generation PZT pressure sensor.

4. Conclusions

We developed an advanced understanding of several new technology areas in MEMS. Manufacturable sol-gel PZT thin film deposition technology has been developed as a piezoelectric “smart” material for advanced applications. A miniaturized PZT-based pressure sensor was fabricated with MEMS technology. Customized stainless steel package allowed the pressure sensor to be tested to a maximum pressure of 40,000 psi. The electrical charge output of the device responded abnormally at the maximum pressure because of packaging issue, not a PZT material performance characteristic. Improvements have been identified and a second generation sensor has been designed for fabrication and testing.

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