EXPERIMENTALLY VALIDATED ALUMINUM NITRIDE BASED PRESSURE, TEMPERATURE AND 3-AXIS ACCELERATION SENSORS INTEGRATED ON A SINGLE CHIP

Fabian Goericke[1]*, Kirti Mansukhani*[1]*, Kansho Yamamoto*[2]*and Albert Pisano*[3]
[1] University of California, Berkeley, USA
[2] Murata Manufacturing Co., Ltd., Kyoto, Japan
[3]University of California, San Diego, USA

ABSTRACT

This paper reports a unified fabrication process used to build multiple Aluminum Nitride (AlN) based micro-electromechanical system (MEMS) sensors on a single chip. A fully functional AlN-based sensor cluster has been demonstrated and is presented in this paper. This sensor cluster is a “five degree-of-freedom” cluster; it measures 3-axis acceleration, temperature and pressure fabricated on a 1 cm x 1 cm die. In addition to utilizing AlN as both the structural and active layer of the sensors, this work is novel because all sensors are fabricated in the same fabrication run.

INTRODUCTION

As MEMS sensor applications have grown from imaging, gaming and smart phones to smart appliances, fitness and health monitoring, there is a growing need for MEMS products to evolve from current SIP (System-in Package) devices to SoC (System-on-Chip) devices to add more functionality at smaller size and cost. Device designs and fabrication processes that support multi-sensor chips are an important step in this direction. The primary advantages of multi-sensor chips are lower cost, smaller footprint, lower power consumption, simpler packaging, and improved performance when compared with their discrete component counterparts. While some silicon based sensor clusters have been developed [1], similar efforts for AlN-based devices seem to be limited. Devices based on the inert, high melting point material AlN can withstand harsh environments including temperatures above 500 °C, high pressures, or reactive media.

SENSOR FUNCTIONAL PRINCIPLES

To integrate the different sensor components into one system, a technology based on resonating AlN sensing elements was selected. Utilizing the piezoelectric properties of AlN enables the excitation and measurement of the changing resonant frequencies.

The principle of operation of the accelerometer lies in the change in resonant frequency of a piezoelectric tuning fork with applied inertial force from a proof mass. The resonant frequency of the tuning forks is extremely big (hundreds of kHz) compared to traditional accelerometers resulting in an improved bandwidth of operation. Using symmetric devices in a differential configuration allows for cancellation of common mode signals, such as temperature and substrate stress. The differential elements are opposing each other and their frequency changes due to acceleration are equal in magnitude and opposite in sign.

The resonant frequency of a membrane over a sealed cavity changes under the influence of a differential pressure across it. This phenomenon is used as the transduction scheme for the pressure sensors on this chip. In order to compensate for temperature effects on the resonant frequency, identical reference sensors are included on every chip that are not subjected to differential pressure. The measurements from the reference sensor can then be used to correct the pressure sensor measurements for temperature.

The temperature sensors built in this sensor cluster are resistive type and utilize the fact that resistance of a metal (in this case Molybdenum (Mo)) changes linearly with temperature. For this application, Mo was used because it provides good linearity over the required temperature range and for ease of fabrication at the Berkeley Nanofabrication laboratory.

FABRICATION PROCESS

An innovative fabrication process using AlN both as the structural and as the active layer of the sensors in the sensor cluster has been developed. The process includes a two-step backside etch of the wafer, which can create very large proof masses for improved acceleration sensitivity. A dual layer AlN process is used to create bimorph structures that can bend out of plane. The resulting triple-beam tuning forks [2] have advantages in electro-mechanical coupling and acceleration sensitivity compared to conventional double-ended tuning forks [3, 4]. The fabrication process is detailed in the following sub-sections.

Photo Mask Design

The fabrication process utilizes 5 photolithography steps. The first three steps are surface micromachining steps on the front side of the wafer and the last two steps are bulk micromachining steps from the backside of the wafer. Projection lithography is used for photoresist (PR) patterning for the three surface micromachining steps. The masks for these steps are shown in Figure 1. The features that are transferred into the AlN/Mo layer stack are shown in brown, the features that are transferred into the top electrode Mo are shown in green, and the features that are etched through the top AlN layer to open contact pads to the bottom Mo layer are shown in blue.

Contact lithography is used for creating the PR patterns on the backside of the wafer. The two photomasks for the bulk micromachining are shown in Figure 2. The photomask on the left side of the figure is used to create the silicon dioxide (SiO_2) hard mask on the wafer backside. These patterns remain for the whole duration of the deep silicon backside etching. The photomask on the right side of the figure shows the areas covered by the PR mask for the first portion of the deep silicon backside etching only. Areas that are open in both masks are etched all the way through to the bottom AlN layer. Areas that are covered by the right mask, but not by the left mask get partially etched and create proof masses for the accelerometers that are thinner than the silicon wafer thickness.

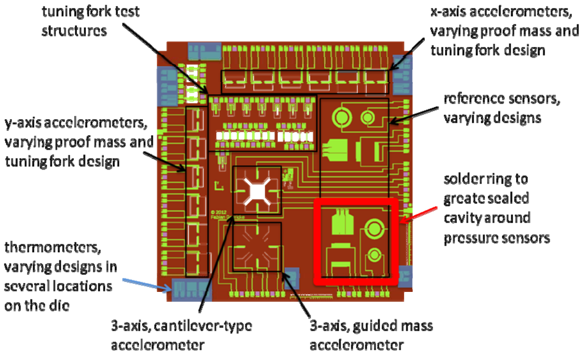

Figure 1: Die-level Mask layout showing Sensor Cluster.

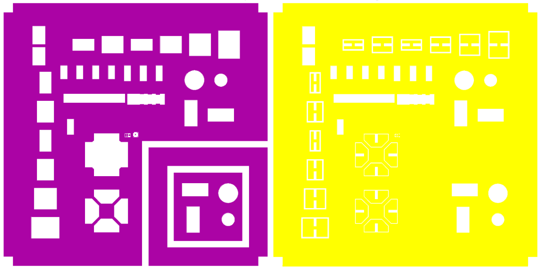

Figure 2: Photomask designs for backside bulk micromachining steps; (L): patterns transferred into the SiO_2 hardmask, (R): patterns transferred into the PR mask to create proof masses.

Process Flow

The fabrication process (depicted in Figure 3) begins with the deposition of the active thin film materials on double-sided polished silicon 15 cm-wafers. The following films are deposited in order: 1 µm AlN, 100 nm Mo, 1 µm AlN, 100 nm Mo, 7.5 nm titanium (Ti).

The two AlN layers form the bi-layer stack that enables out-of-plane motion of the devices when one of the layers is actuated independently from the other. In this case, the top AlN layer is the active layer that is actuated and sensed. The first Mo layer serves as a continuous bottom electrode to the active AlN layer. It is not patterned specifically, but gets etched in a self-aligned manner along with the AlN structure. The top Mo layer is a patterned metal layer that allows the formation of areas specifically for piezoelectric driving and sensing. The Ti film promotes the adhesion of the PR on the top layer.

Subsequent to the thin film deposition, PR is spun on the wafers, and patterned via projection lithography. The PR is then hardbaked (heat and UV). The PR patterns are transferred into the top Mo layer using reactive ion etching (RIE) with good selectivity to the underlying AlN film. The PR is then removed and a short blanket etch is performed to remove the thin layer of Ti on the Mo electrodes.

PR is patterned as a continuous film with small square opening in selected places. It is hardbaked and used as a mask for wet etching the top AlN film. An ammonium hydroxide dip followed by a heated phosphoric acid bath is used to etch the AlN with good selectivity to the underlying Mo film. After removal of the PR, a 1.85 µm film of SiO_2 is deposited on the wafer. This film is used for two purposes. On the front side of the wafer, it is used as a hardmask for the patterning of the AlN devices. On the backside of the wafer it is used as a hardmask for etching the silicon to create trenches and proof masses.

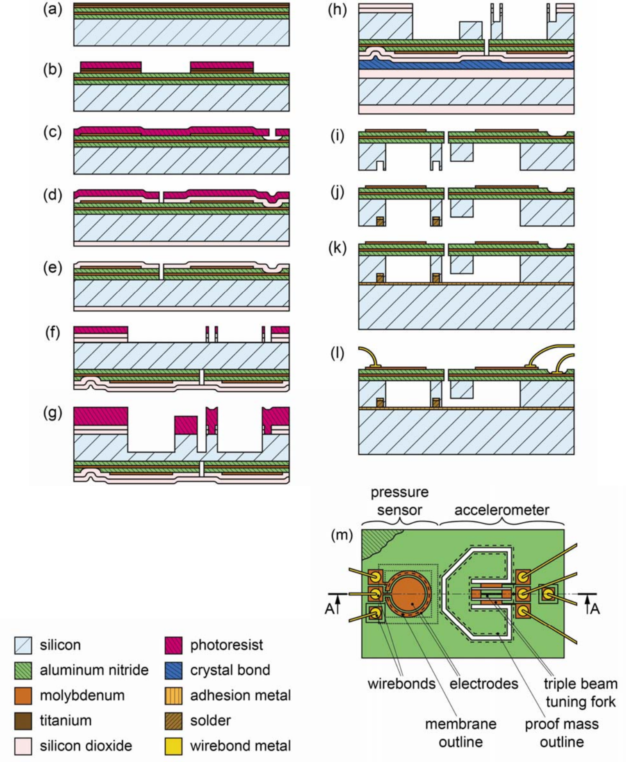

Figure 3: Abridged fabrication process for Sensor Cluster.

PR is patterned via projection lithography in the shape of the device outlines (tuning forks, etc.). The patterns are aligned to the top electrode features already present on the wafers. This is the most critical alignment step in the fabrication process as even small misalignments (greater than about 0.25 µm) can greatly affect the device performance. Areas that are especially critical are the small current traces on the out-of-plane tuning fork. However, the requirement is somewhat more relaxed than it would have been for in-plane tuning forks, as those devices would require much narrower beam widths. After PR patterning and hardbaking the pattern is transferred into the SiO_2 via RIE. Then the PR is removed in an oxygen plasma and the pattern is transferred from the SiO_2 hardmask into the AlN/Mo/AlN layer stack via another RIE process. This two-step etching process, which first creates a hardmask and then etches the device layers has been found to produce better feature reproduction and steeper sidewalls than using a single PR mask alone.

PR is patterned on the backside of the wafer via contact lithography. The features are aligned to the top electrode patterns on the frontside of the wafer via backside alignment. The PR is then hardbaked and the pattern is transferred into the SiO_2 layer via RIE. The PR is removed. The resulting SiO_2 patterns are the etch mask for the second deep silicon etch step on the backside of the wafer.

Thick (6 µm) PR is deposited on the backside and patterned via contact lithography. The alignment is performed with respect to the SiO_2 patterns already on the backside. The hardbake of this PR layer is performed in an oven for an 120 minutes at 120 ºC (without UV light). Then deep silicon etching (Bosch process) is employed to transfer the PR pattern into the silicon wafer. After a period of time the PR is consumed and only the SiO_2 acts as a masking layer for the remainder of the etching. By using two masking materials together at first and only one mask in the end, two different etch depths are achieved. This process results in the through etch to the AlN film in some areas, while leaving silicon blocks in other areas that are used as proof masses for the accelerometers. When about 400 µm of etch depth is achieved the etching is interrupted to bond the wafer to a handle wafer.

A handle wafer is prepared by depositing about 4 µm of SiO_2 on it in a low temperature chemical vapor deposition (CVD) process. The handle wafer is heated and "crystal bond" is melted on its surface. The device wafer is then placed on the handle wafer and the wafer stack is cooled down slowly. The "crystal bond" forms a solid bond with good thermal conductivity once it hardens upon cooling.

Deep silicon etching is performed until silicon is removed in all desired areas. The device wafer is detached from the handle wafer by submersion in acetone. Since the deep silicon etching is also used to separate the individual sensor cluster chips from each other, the chips are now floating separately in the acetone. The individual chips are picked out of the acetone and transferred to a secondary acetone bath, then to an isopropanol (IPA) bath. The chips are removed from the IPA bath and put in a drying area. Once the IPA has evaporated, gaseous hydrofluoric acid (HF) is used to remove the SiO_2 layer from both front and back sides of the chips. The chips are then placed in "gelpak" chip carriers for temporary storage. All subsequent processing steps are on an individual chip basis.

A stack of tin and gold is deposited on the backside of the device chip and on a carrier chip. A solder preform is manually deposited on the device chip and the device chip is placed on the carrier chip. The chip stack is placed on a hotplate to melt the solder and create a permanent bond that creates the hermetic air cavity underneath the pressure sensors. The chip stack is then glued into a ceramic carrier and the desired devices are wire-bonded to the ceramic carrier's contacts. The ceramic chip carrier creates the interface to printed circuit boards.

TESTING

One device each for the pressure, temperature and inertial sensors have been tested so far and the results have been summarized in the following sections.

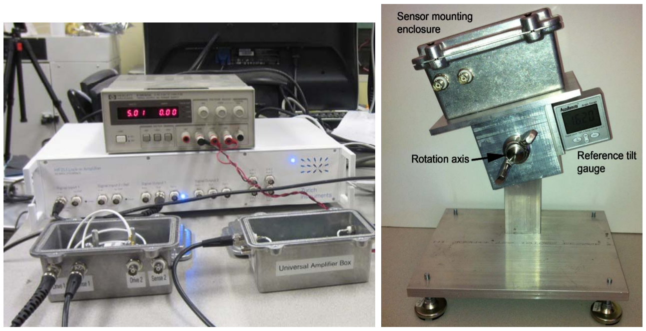

Figure 4: (L) Test Setup for actuation and sensing of devices. (R) Tilt setup for accelerometer testing

Each of the inertial and pressure sensors are operated as a 2-port piezoelectric resonator. Each channel is operated in a phase-locked loop (PLL) setup. The output of the PLL is connected to the drive port of the channel. The sense port of the channel is connected to a pre-amplifier that consists of a transimpedance amplifier to convert the output current into a voltage and a second stage that amplifies this voltage. The output of the pre-amplifier is phase-shifted and fed into the feedback port of the PLL. The PLL in conjunction with the phase shifter keeps the phase shift between the drive and sense ports of the sensor constant and thus lock to a specific pre-defined resonance frequency. The Zurich Instruments HF2LI measurement tool combines the functions of the phase shifter, PLL and frequency counter and is convenient to use for laboratory testing. The experimental setup is shown in Figure 4.

The accelerometer is operated at the resonant peak close to 460 kHz. The phase shifter for the subsequent measurements is set such that a phase relation of 0° is kept between sensor drive port and pre-amplifier output.

The same setup procedure was repeated for Channel B before the sensitivity characterization of the devices was performed. For the acceleration sensitivity testing, the sensor chip was mounted inside a rotatable enclosure with a reference tilt gauge (Figure 4). By turning the enclosure around a fixed axis of the sensor chip the acceleration on the sensor chip can be varied from +1G to -1G.

The operating frequency of the pressure sensor and reference sensor membranes is around 30 kHz. The sensor cluster chip was mounted in a vacuum chamber. The vacuum chamber was pumped down to about 0.6 atm and brought back to atmospheric pressure by stepwise filling with nitrogen. At each pressure level, the frequencies of the pressure and reference sensor were monitored.

For temperature testing, the sensor was mounted inside of a TPS Tenney environmental test chamber and connected to a Wheatstone bridge circuit.

RESULTS

Scanning electron microscope (SEM) images of each of the major sensors fabricated and tested as part of the sensor cluster are shown in Figure 5. The resonant accelerometers operate at about 460 kHz. Figure 6 shows that the y-axis acceleration sensitivity is 8708 Hz/G with good linearity in the measured range. The cross-axis rejection factor to the x-axis is about 100. The z-axis acceleration sensitivity is 7300 Hz/G (Figure 7). The pressure sensor has an operating frequency of about 30 kHz and a sensitivity of 250 Hz/psi. The reference sensor is significantly less sensitive to pressure changes than the pressure sensor (Figure 8), which enables it to be used for temperature compensation. The temperature sensor exhibits good linearity and a temperature sensitivity of 1.625 mV/°C (Figure 9).

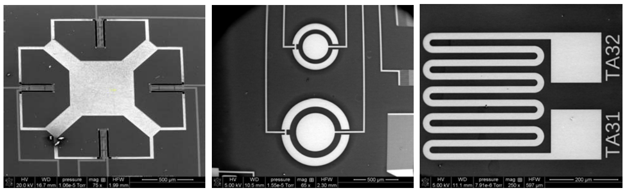

Figure 5: (L) SEM of 3-axis Accelerometer with 4 proof masses, each connected to the substrate by a tuning fork sensing element; (M) SEM of Bulk membrane pressure sensors; (R) SEM of Temperature sensor

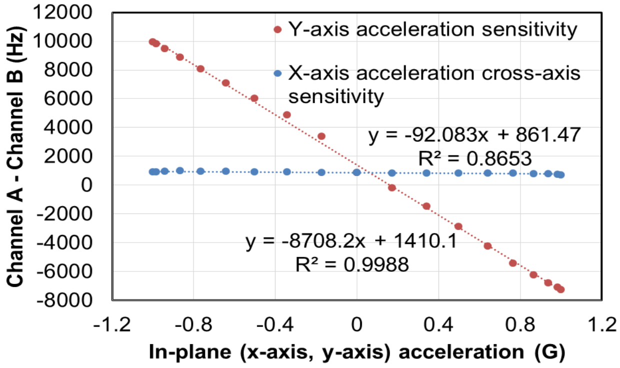

Figure 6: Measured Y-axis sensitivity and x-axis cross-axis sensitivity of 3-axis accelerometer.

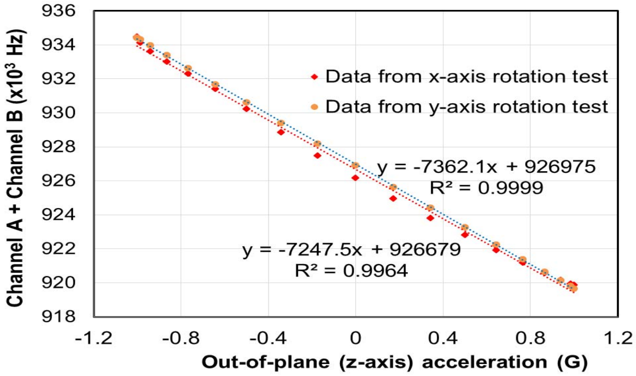

Figure 7: Measured Z-axis sensitivity 3-axis accelerometer.

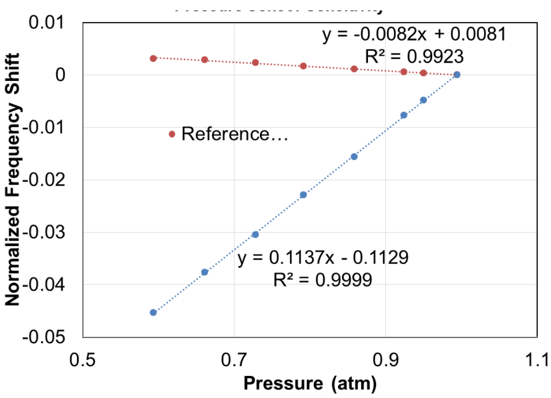

Figure 8: Measured Pressure Sensor Sensitivity.

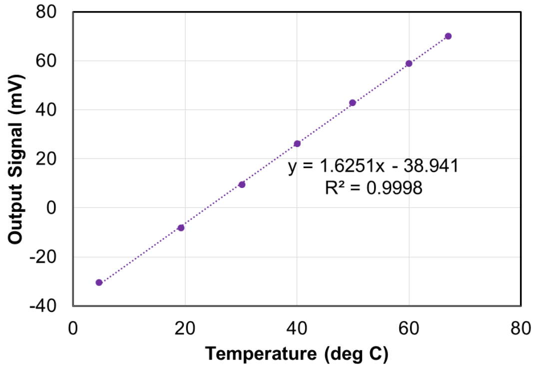

Figure 9: Measured Temperature Sensor Sensitivity.

CONCLUSIONS

A unified fabrication process used to build a fully functional "five degree-of-freedom" AlN based MEMS sensor cluster has been presented in this paper. The sensor cluster has been used to measure 3-axis acceleration, temperature and pressure and the preliminary experimental results have also been presented.

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CONTACT

K. R. Mansukhani, tel: +1-617-7805282; kirti@berkeley.edu