ABSTRACT

Aluminum nitride (AlN) is a promising material for harsh environment sensing applications due to its piezoelectric effect and mechanical stability at high temperatures. In this work, AlN double-ended tuning forks (DETF) are presented as a transduction element to measure mechanical loads by observing the resonance frequency shift. The fabrication process of the MEMS devices including the bonding step to a steel parallel is described. Device operation is demonstrated for strain sensing up to 91 °C and operation of the transducer without applied strain is demonstrated up to 570 °C.

KEYWORDS

aluminum nitride, double-ended tuning fork, high temperature, strain sensing

INTRODUCTION

DETF devices based on silicon have been shown to be highly sensitive strain sensors [1]. Because of their small size they can be used to measure localized strain fields [2]. These silicon-based sensors rely on electrostatic actuation and capacitive readout and require large actuation and bias voltages. They also require special circuitry, such as square wave oscillators, in order to be capable of operating in air due to the large damping of their comb fingers [3].

In contrast, AlN-based piezoelectric DETF devices can be operated with standard resonator circuits in air using very small actuation voltages. When used as strain sensors, as demonstrated for the first time in this work, they require very small chip area due to the lack of comb fingers. Therefore, measurements of strain gradients over a very small area using an array of such devices are conceivable. Besides the reduced form factor and enhanced operation at atmospheric pressure, harsh environment survivability is another major advantage of the AlN DETF sensors of this work. It is known that AlN preserves its piezoelectric properties up to 1150 °C [4]. Unlike polysilicon, AlN is also mechanically stable at and above this temperature [5]. An overview of the sensor design and the experimental setup is shown in Figure 1.

FABRICATION

The fabrication process of the DETF sensor is shown in Figure 2.
The substrate is a standard 150 mm, p-type silicon wafer. First, a 300 nm thick insulating layer of silicon nitride (SiN) is deposited in an LPCVD process (a). Then, the 100 nm platinum (Pt) bottom electrode patterns are formed using a standard lift-off process with electron beam evaporation (b). The Pt adhesion is improved by a thin layer of chromium (Cr). Next, a 1.9 µm layer of highly c-axis oriented, polycrystalline AlN is deposited using a reactive AC sputtering process (c). Then, the Pt top electrode is patterned using the same lift-off process as for the bottom electrode (d). Wire-bonding access to the bottom electrode is opened by wet-etching the AlN with hot phosphoric acid (e). Next, a 1 µm layer of silicon dioxide (SiO) is deposited using a LPCVD process and dry-etched in a reactive ion etching (RIE) tool. This SiO-layer forms the hardmask for the subsequent dry-etching of the AlN (f). A scanning electron micrograph of the layer stack’s cross-section after RIE of the AlN is shown in Figure 3. It can be seen that a sidewall angle of 10° is achieved with this process.

After wafer-dicing, the devices on the individual MEMS dies are released by timed etching of the silicon substrate in xenon difluoride (g). For the strain sensing experiments, the MEMS die is bonded to a steel parallel. A layer stack starting with titanium followed by nickel and gold is electron beam evaporated onto the backside of the MEMS die. The thicknesses of the three layers are 25 nm, 400 nm, and 10 nm, respectively. The steel parallel is prepared by abrasive removal of the oxide layer followed by application of a layer of tin-based solder using a stencil (h). The MEMS die is then placed on the steel parallel and bonded using rapid, localized inductive heating for 8 seconds. A resistive, on-chip temperature sensor is fabricated along with the DETF sensor. For this purpose, the bottom electrode layer is used as the resistive meander trace and the AlN is used as protective and insulating layer. Since the bottom electrode is made of Pt, a very linear behavior of resistance with temperature over a large temperature range is achieved. Both the DETF strain sensor and the resistive temperature sensor are shown as insets in Figure 1.

**DEVICE CHARACTERIZATION**

**Device Impedance and Resonant Mode Shapes**

The impedance amplitude and phase were measured at atmospheric pressure using a network analyzer and a simple pre-amplification circuit. Due to the design of the electrodes on the DETF, in-plane resonance mode shapes are much more easily excited than out-of-plane mode shapes. The first three dominant mode shapes were determined using the commercial finite element modeling (FEM) software ANSYS and are shown as insets in Figure 4. Their resonance frequencies are within 10% of the measured values from the network analyzer, whose amplitude and phase are also given in Figure 4. It can be seen that the first mode shape has a much larger phase than the other two and it is used for the measurements in the subsequent experiments.

![Figure 3. Cross-sectional view of the layer stack after dry-etching of the AlN layer.](image)

![Figure 4. Impedance amplitude and phase of the three dominant modes measured in air and their mode shapes determined by finite element modeling.](image)

**Strain Sensitivity**

For the measurement of the strain sensitivity, the steel parallel with the bonded MEMS die is clamped on one end and a defined deflection is applied to the other end as shown in Figure 1. The temperature is controlled by placing the entire setup inside an environmental chamber. Prior to the experiment, a steel parallel with a bonded dummy silicon chip of the same dimensions as the MEMS die is used to calibrate the strain as a function of the applied deflection. For this purpose, a commercial strain gauge is attached to the dummy chip in the same location that the DETF strain sensor occupies on the MEMS die using standard epoxy adhesive.

In the experiment, the strain is increased in steps of about 5 µε every 5 minutes and the frequency of the DETF strain sensor is constantly monitored. To verify the stability of the frequency measurement, the strain is then reduced back to zero in the same steps. The frequency output at room temperature for this
The same experiment is then repeated for three additional temperatures of 45, 68, and 91 °C. The frequency output is shown as a function of applied strain for all temperatures in Figure 6.

Although the noise level of the device has not been measured, the data clearly indicates sub-microstrain resolution of the DETF device. The strain sensitivity increases with temperature and ranges from from 192 ppm/µε at 22 °C to 243 ppm/µε at 91 °C.

High Temperature Operation

Another aspect of this work is the demonstration of operating the AlN DETF sensor at high temperature to prove usability for harsh environment sensing applications. For this purpose, a MEMS die not bonded to a steel parallel is mounted in a ceramic package. The chip is temporarily held in place by carbon paste to connect the wire-bonds. During the high temperature experiment this bond detaches and the die is held in place only by the bond wires. In this way, no thermal stresses from the ceramic package can be coupled into the strain sensor and the unaltered behavior of the MEMS die itself is tested. Prior to the experiment, the resistance of the on-chip Pt temperature sensor is calibrated in a temperature chamber. The signal from the Pt sensor is used to monitor the actual temperature on the MEMS die during the experiment. The temperature is increased by focusing a high power IR-lamp on the surface of the MEMS die. The power is slowly increased until the on-chip temperature reaches 600 °C and then decreased back to near room temperature. The total time for each cycle is about 20 minutes and the experiment is repeated for a total of three cycles. The resonance frequency of the AlN DETF and the temperature measured by the on-chip sensor are shown in Figure 7.

It can be seen that the AlN DETF is operational up to a temperature of 570 °C. For higher temperatures, the readout circuit was not able to lock to the DETF’s resonance frequency. These areas are shown with dotted lines in the figure. This behavior is assumed to be caused by the increase in noise level at high temperatures in combination with the long cable connections required for the high temperature setup. An improved setup in which the circuit can be placed close to the device without getting damaged by the high temperature can be used to detect the true temperature limit of the DETF sensor in the future.

The DETF’s resonance frequency as a function of temperature during the cooling phases of all three cycles is shown in Figure 8. It can be seen that the temperature-dependent behavior of the resonance frequency is highly repeatable. With increasing temperature, the resonance frequency initially decreases because of the compressive stress coupled into the DETF from the silicon substrate which has a lower coefficient of thermal expansion (CTE) than AlN. At a temperature of 315 °C, however, a minimum in the resonance frequency is observed. The
The possibility of a change in resonance mode at the turnover point could also be ruled out from FEM analysis. Finally, all relevant materials have negative thermal coefficient of elastic moduli, which should also result in a steady decrease in resonance frequency with increasing temperature. Further testing needs to be performed to investigate this unexpected behavior.

**CONCLUSION**

A new type of strain sensor based on piezoelectrically actuated aluminum nitride double-ended tuning forks has been fabricated and bonded to a steel parallel. Strain sensing experiments indicate high strain sensitivity of 192 to 243 ppm/µε. High temperature testing verified that the DETF can be operated to at least 570 °C and it is expected that higher temperatures can be achieved with appropriate circuitry.

This type of transducer can be used as the sensing element for a variety of mechanical sensors, e.g. accelerometers, gyroscopes, and pressure sensors. Due to its capability to operate at high temperature, new harsh environment sensing applications are conceivable. In combination with high temperature circuitry, such sensors could operate inside of combustion engines, turbines, or geothermal wells.

**REFERENCES**


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