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A robust pressure sensor for harsh environmental applications

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ABSTRACT

Due to economical and environmental requirements there is a strong need both to increase the efficiency and to monitor the actual status of gas turbines, rocket engines and deep drilling systems. For these applications a micromachined pressure sensor based on a sapphire body and a platinum thin film metallization is presented to withstand harsh environments such as high temperature levels, aggressive media and/or high pressure loads. For pre-evaluation purposes, a reusable packing is used enabling the device characterization in a very efficient way up to temperatures of 440 °C and pressures of 30 bar, respectively. As expected, the output signals of the Wheatstone bridge increase with higher pressures, but decrease with enhanced temperature levels. Furthermore, these characteristics show a sensitivity of about 10 μV/(V bar) in this temperature range and a negative drift in the offset when no pressure load is applied with increasing temperature. This effect is predominantly caused by the mismatch of the temperature coefficients of expansion associated with the device and the housing leading to a pre-stressed membrane.

1. Introduction

The monitoring of absolute pressure and pressure changes in combustion engines such as gas turbines, jet and rocket engines is a very challenging task. Nevertheless the characterization of the pressure in the combustion process of these engines is an important key to drive the development for higher power density and efficiency [1,2]. The presence of harsh environmental conditions typically comprising a combination of high temperature, high pressure and aggressive media strongly limit the use of pressure sensors based on silicon (Si) MEMS technology [3]. In the last 15 years, especially silicon carbide (SiC) pressure sensors were in the focus of several research activities to overcome the limitations of Si technology for such applications [4,5]. Despite the outstanding properties of SiC making this material an interesting candidate both the long-term stability of ohmic contacts to SiC and the different materials with their specific temperature dependence which need to be combined with the semiconductor sensor body for robust packaging approaches are most challenging [6,7]. Another approach reported in standard literature comprises the use of sapphire as high temperature stable, chemically inert and dielectric substrate. To sense the pressure the low fatigue characteristics of monocrystalline Al_2O_3 membranes even under harsh environmental conditions is most beneficially combined with the piezoresistive properties of monocrystalline silicon. But, reliable operation is still limited to a maximum temperature load up to about 400 °C even when a capacitive sensing principal is applied thus avoiding any semiconductor–metal junction which is one of the most probable sources of device failure during operation [8–10].

It is the objective of this work to investigate the performance of a micromachined pressure sensor based on sapphire having strain gauges made of platinum to avoid a metal–semiconductor contact and hence, to increase temperature resistance and the long-term stability of the device. Furthermore, the metallization is evaluated at high temperatures up to 800 °C for several hundreds of hours to ensure stability during device characterization and to identify in advance drift effects for future operation scenarios.

2. Sensor fabrication and experimental details

Due to its outstanding dielectric stability and mechanical robustness even at high temperatures sapphire substrates with a crystallographic orientation perpendicular to the *c*-axis are selected as substrate material. The diameter is 50 mm at a nominal thickness of 2 mm. For planes perpendicular to the *c*-axis the TCE (temperature coefficient of expansion) is about $\alpha = 6.9 \cdot 10^{-6}\,K^{-1}$ in the temperature range from 0 °C to 427 °C [11], whereas for comparison purposes the corresponding value is $13.2 \cdot 10^{-6}\,K^{-1}$ between

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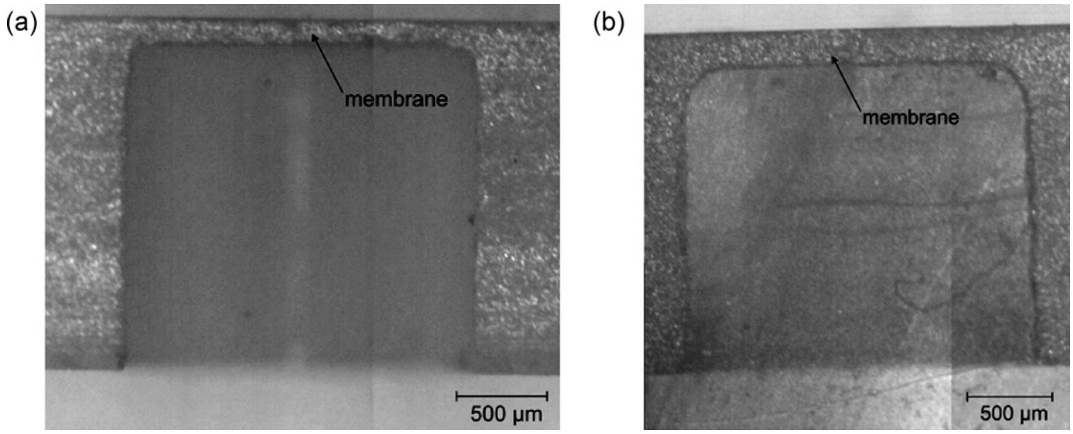

Fig. 1. (a) Cross-sectional view on a sapphire membrane (thickness: 160 μm) applying ultrasonic-assisted drilling technique for patterning. (b) Cross-sectional view on a sapphire membrane (thickness: 215 μm) formed with a purely abrasive drilling technique. More rounded edge geometries result.

room temperature and 400 °C for high temperature stable nickel-based superalloys such as HAYNES® 230® [12]. As the patterning of sapphire is very challenging [13,14] two different techniques well-known from precision engineering were evaluated in advance applying a diamond tool when targeting a membrane with a final thickness of about 200 μm for the pressure sensor.

Fig. 1a shows in a cross-sectional view the membrane geometry which results when using an ultrasonic-assisted drilling approach. The ultrasonic-assisted drilling equipment is similar to a high-precision milling machine and offers a position accuracy of ±2.5 μm. In order to handle larger substrate sizes (i.e. wafers) a vacuum chuck can be utilized. Compared to a purely abrasive drilling technique (see Fig. 1b), ultrasonic drilling offers some advantages, as it is less time and cost consuming. In the latter case, however, the rotating tool transfers an enhanced mechanical load to the surface of the sapphire substrate during machining. With decreasing membrane thickness problems arise as the membrane becomes fragile and hence, tends to break. Furthermore, the tool itself shows a high wear, especially in the area of the edges. This leads to strongly rounded edge characteristics with radii r_e in the range of 200 μm at the transition region to the sensor body, as observed in Fig. 1b. With proceeding wear of the tool the contact area decreases and the load can exceed the upper, limiting value leading to a complete failure of the device. In contrast, the mechanical load on both tool and work piece is substantially lower in ultrasonic drilling minimizing wear effects and resulting in sharper edge geometries with edge radii of about 50 μm. Despite these advantages, it is advisable to perform a surface finishing procedure on the machined side of the membrane with low ultrasonic power, low feed rate and a more abrasive drilling at low load to reduce to a minimum any surface-near defects which can act in this brittle material as origin for cracks when the device is pressure loaded during operation. Doing so, an enhanced surface quality, a higher yield in device fabrication and an enhanced long-term stability results compared to conventional techniques, so that all sensor elements investigated in this work are patterned with this technique.

The strain gauges consist of a 1 μm thick platinum film, deposited without any adhesion promoter on the sapphire substrate with a rate of about 50 nm min^{-1} at a back pressure of $3 \cdot 10^{-3}$ mbar in pure Argon atmosphere. Prior to the Pt deposition the sapphire surface was cleaned in situ at an RF power density of 1 W cm^{-2} for 7 min using the reverse etching mode. By this procedure, the adhesion strength of the Pt thin film is substantially enhanced due to a chemical activation of the sapphire surface. In all experiments the substrates were nominally unheated during deposition. At a plasma density of 4 W cm^{-2}, however, a self-heating effect has to be taken into account resulting in a moderate temperature increase to about 120 °C during Pt film deposition. After having done a standard lithography using a 1.2 μm thick resist (AZ 1514H) the meander-shaped strain gauges were patterned with a conventional Argon-based dry-etching technique (TePla RIB Etch 250) to form a Wheatstone bridge. The resist is stripped in a plasma asher (TePla 300-M) at a power of 300 W for 15 min. The sensor chips with a diameter of 8 mm were cut out of the sapphire substrate with the previous mentioned ultrasonic-assisted drilling process. To reduce drift effects and to increase the adhesion of the Pt metallization by an enhanced formation of oxygen bonds at the interface between Pt and sapphire the complete assembly is pre-annealed for 30 min in air either at 600 °C or at 850 °C (see Section 3.2). The position and the design of the meander-shaped strain sensitive elements with respect to the membrane are optimized using FEA (finite element analysis) and CAD (computer aided design) taking into account the rounded edge characteristics. In order to reduce the noise of the Wheatstone bridge, the aspect ratio of length to width is maximized for the resistors. Detailed analyses demonstrate that with increasing radii the boundary area to the sensor body gets stiffer shifting the location of the maximum radial strain component to the centre of the membrane while simultaneously decreasing this value. The tangential strain component is quite insensitive with respect to this geometrical parameter resulting only in a slight decrease while keeping the overall characteristics. In Fig. 2, an optical micrograph of a typical pressure sensor design is shown. To determine

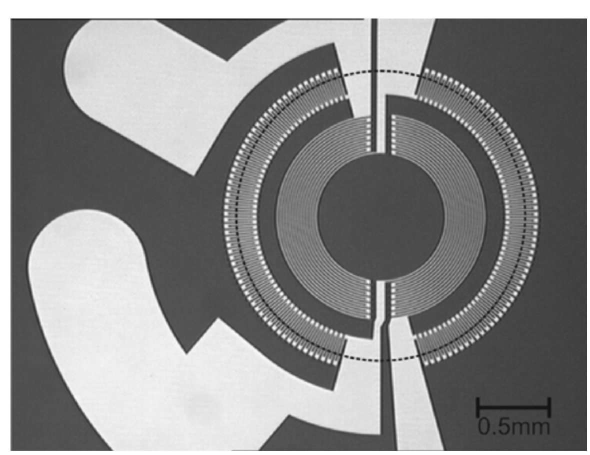

Fig. 2. Meander-shaped strain gauges made of platinum on a sapphire membrane. The dashed line indicates the area of the membrane.