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HIGH TEMPERATURE (800°C) MEMS PRESSURE SENSOR DEVELOPMENT INCLUDING REUSABLE PACKAGING FOR ROCKET ENGINE APPLICATIONS

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ABSTRACT

For aircraft and rocket engines there is a strong need to measure the pressure in the propulsion system at high temperature (HT) with a high local resolution. Miniaturized sensor elements commercially available show decisive disadvantages. With piezoelectric-based sensors working clearly above 500°C static pressures can not be measured. Optical sensors are very expensive and require complex electronics. SiC sensor prototypes are operated up to 650°C, but require high technological efforts. The present approach is based on resistors placed on top of a 2 mm diameter sapphire membrane (8 mm chip diameter). The strain gauges are made either of antimony doped tin oxide (SnO_2:Sb) or platinum (Pt). This material combination allows for matching the thermal coefficients of expansion (TCE) of the materials involved. The morphology of the SnO_2:Sb layer can be optimized to reduce surface roughness on the nanometer scale and hence, gas sensitivity. Antimony doping increases conductivity, but decreases the gauge factor. With this nanotechnological knowledge it is possible to adjust the material properties to the needs of our aerospace applications. Tin oxide was shown to be very stable at HT. We also measured a 2.5% change in electrical

resistivity at room temperature at maximum membrane deflection. The maximum temperature coefficient of resistivity (TCR) is less than $3.5 \cdot 10^{-4}$ K^{-1} in the temperature range between 25°C and 640°C.

In addition to the device related research work, a novel reusable packaging concept is developed as housing is the main cost driver. After the chip is destroyed the functional device can simply be replaced – housing and contacts can be reused. The MEMS device is electrically contacted with a miniaturized spring mechanism. It is loaded from the harsh environment side into the HT stable metal housing. A cap is screwed into the housing and compresses the inserted seal ring against the chip. The part for electrical contacting on the opposite housing side is not disassembled. The MEMS device is not in direct contact with the housing material, but embedded between two adaptive layers of the same material as the device (sapphire) to decrease thermally induced mechanical stress. Overall weight is 46 g. This packaging concept has been successfully optimized so that the whole assembly can withstand 800°C and simultaneously provides sealing up to 250 bar! After testing in such harsh environment, the small packaging can still be unscrewed to exchange the MEMS device. Due to the reutilization, the packaging can be used far beyond the lifetime of HT MEMS devices.

INTRODUCTION

Pressure sensors for propulsion applications have to fulfill many challenging requirements simultaneously. For example, direct contact of the sensor element to the harsh environment (HE) has to be ensured in order to measure the pressure level and therefore, it has to withstand the corrosive gases, high temperature and high pressure loads present in the propulsion system. The packaging should be tiny enough for not disturbing other measurements, e.g. vibrations. Therefore, tailored material development and combination are the most challenging part in the sensor design. Noble metals, superalloys, glasses, single crystal materials and ceramics have to be considered. But often a mismatch of TCE excludes the combination of these materials, or large efforts have to be made to reduce the thermally induced stresses. In case of piezo-resistive sensors the strain gauge material should show a low as possible thermal coefficient of resistance and the TCE has to match with the substrate material. In the following we will present a pressure sensor which is designed as far as possible in accordance to these requirements. The sensor element is based on a sapphire substrate with strain gauges made of antimony doped tin oxide or Pt housed in a packaging made of a Ni based superalloy.

This sensor system can be used in the further development of propulsion systems to save costs and time. Furthermore, it might find applications in the in-flight monitoring of the engine status. Other applications could be in the field of oil exploitation, especially in deep drilling, and even in the automotive sector where new combustion processes may lead to conditions during operation matching those of the proposed sensor. However, in the last application costs are a major concern. All state-of-the-art sensor systems operated as transducers converting mechanical quantities to electrical signals do not fulfill the requirements in weight, measurement accuracy and the possibility to measure static and dynamic pressures with one single sensor element. Optical sensor systems fulfilling these requirements are extremely expensive (e.g. above € 5000) because of the high-level evaluation electronics needed.

SENSOR PACKAGING

Packaging of MEMS devices often plays a key role for a successful product development, especially in HE applications. During the development phase of a MEMS device, it is important to analyze the device after exposure to HE. For this reason, a reusable packaging was developed for the HE pressure sensor. In application a failure of the sensor system is usually caused by a failure of the MEMS device. In contrast the overall costs of the sensor product are determined by the costs for the packaging. Therefore, it is a cost-saving method to reuse the packaging even after leaving the development phase.

The packaging, as shown in Fig. 1 [1], is fabricated from a Ni based superalloy (Haynes 230). It can be screwed in a 14 mm opening of the propulsion system.

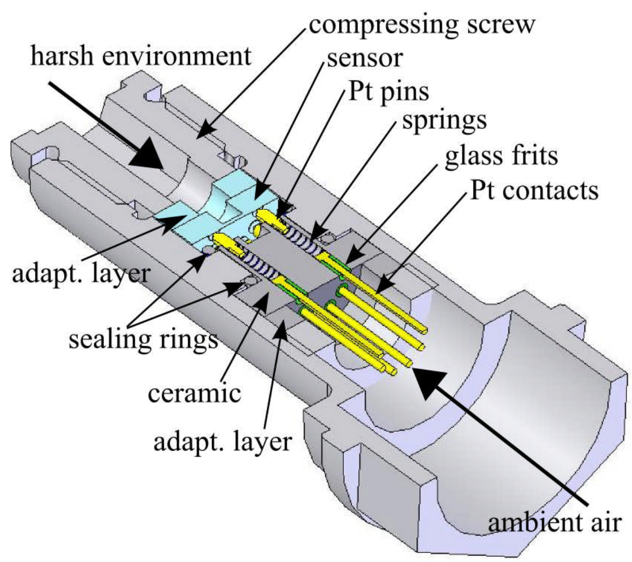

Figure 1: Sectional view on the sensor packaging assembly.

The MEMS device is loaded from the HE side of the packaging, therefore, the contact part, which is loaded from the opposite side, does not have to be demounted when changing the sensor device.

Sealing against gases from the HE is assured by a gas filled metal sealing ring covered with gold. This sealing ring is mounted between the packaging and the sensor element. On top of the sensor adaptive layers are implemented to reduce the mechanical stress on the sensor caused by mismatch of the TCE of sensor and packaging. The assembly of adaptive layers, sensor and sealing is fixed by the compressing screw.

The contact part is fabricated in an Al_2O_3 ceramic. This material offers a good electrical insulation even at very high temperatures. The sealing between the packaging and the contact part is again performed by a gas filled sealing ring. Therefore, the surface of the ceramic has to be polished to show an average surface roughness $R_a < 0.4$ µm. The electrical signals of the sensor can be read out by contacts made of Pt. The sealing between these Pt pins and the ceramic body is done by glass frits which have a high melting point (~1000°C) and a TCE close to Pt and Al_2O_3. The Pt pins are connected to a miniaturized spring mechanism consisting of Inconel X750. The spring has a diameter of 1 mm pressing the Pt pins on the contact pads of the MEMS sensor.

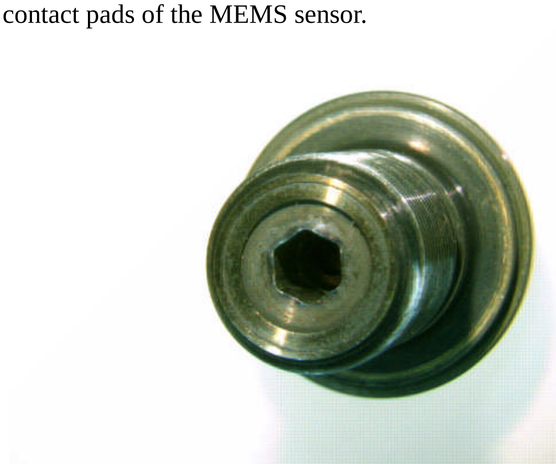

Figure 2: Test packaging after about one week of leakage test simultaneously stressed from RT to 600°C.

This sensor housing shown in Fig. 2 has been tested successfully at pressure loads of up to 250 bar and temperatures up to 800°C simultaneously. The sealing tests have been performed in a modified laboratory furnace with a connection to a nitrogen gas system (see Fig. 3).

In measurements over more than 16 hours at temperatures up to 400°C the leakage rate is independent from the applied back pressure and below the measurement accuracy (MA).

The onset of leakage is detected at 600°C when a pressure level of 175 bar is applied. For higher temperatures a leakage rate of around $5 \cdot 10^{-3}$ mbar·l/s has to be expected (see Tab. 1).

Figure 3: Sensor packaging in a laboratory furnace and simultaneously loaded with pressure up to 300bar.

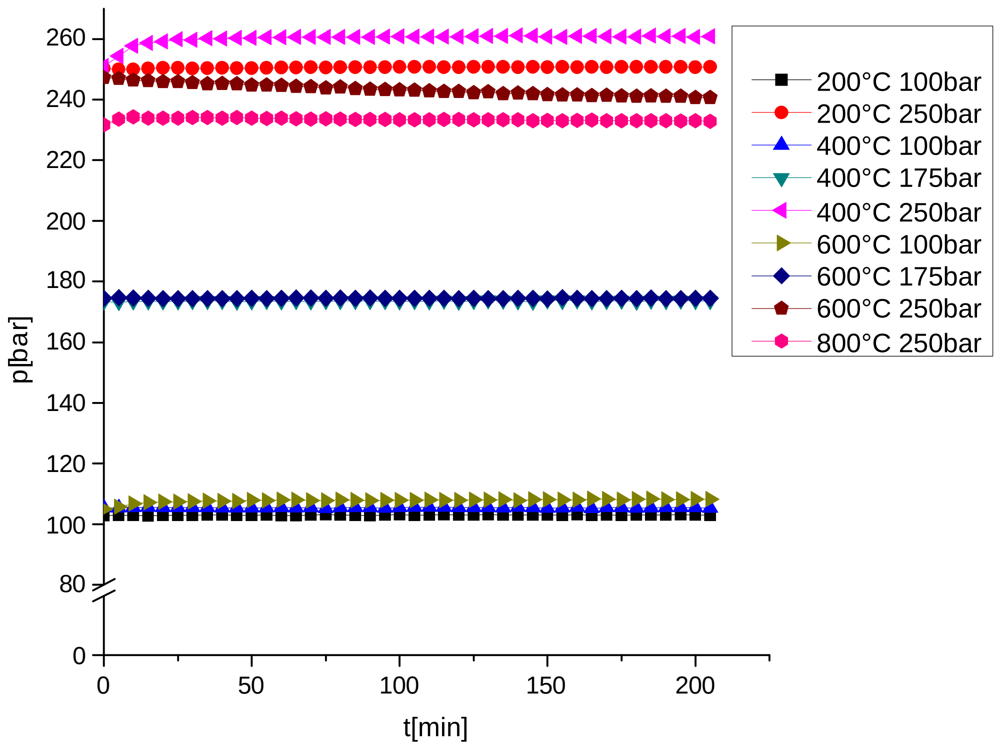

Figure 4: Pressure measured in a closed cavity between packaging and pressure calibrator.

Table 1: Leakage rate determined by measuring the pressure drop in a closed cavity.

Temperature [°C]	Pressure [bar]	Leakage rate [mbar·l/s]
200	100	<MA
200	250	<MA
400	100	<MA
400	175	<MA
400	250	<MA
600	100	<MA
600	175	$1.0 \cdot 10^{-4}$
600	250	$6.25 \cdot 10^{-3}$
800	250	$5.21 \cdot 10^{-3}$

SENSOR DEVICE

The sensor principle is piezo-resistive, alternatively strain gauge based, therefore dynamic and static pressures can be measured. The piezo-resistive strain gauges are deposited on the sapphire membrane by physical vapor deposition processes (PVD). Membranes with a thickness of 100 µm and 2 mm in diameter were fabricated in the sapphire substrate (see Fig. 5).

Sapphire is chemically inert to many aggressive gases and liquids and therefore, it can be used in a propulsion system.

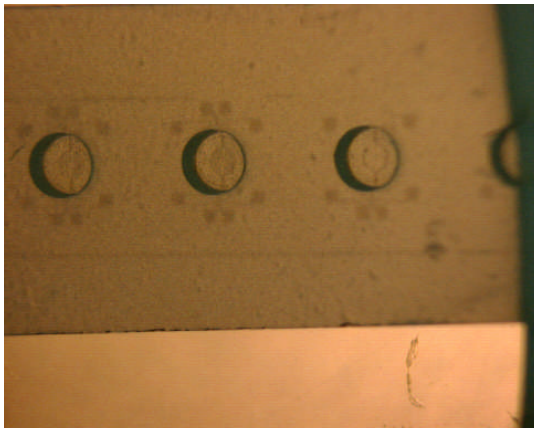

Figure 5: Membranes in a sapphire substrate and structures of the strain gauges (membrane diameter: 2mm).

Furthermore sapphire is an excellent insulator at high temperatures and therefore, electrically conductive strain gauges can be deposited directly on the sapphire surface. Capacitive pressure sensors based on sapphire have been successfully demonstrated at lower pressures and temperatures [2].

Strain gauges are fabricated from SnO_2:Sb or Pt. Both materials show a TCE close to the TCE of sapphire and therefore, the strain resulting from thermal expansion is minimized. Furthermore, Pt is known for its almost linear TCR and the offset resulting from temperature changes is predictable. SnO_2:Sb thin films exhibit a promising stability at high temperatures [3]. As shown in Fig. 6, the TCR of SnO_2:Sb is determined to be $3.5 \cdot 10^{-4}$ K^{-1} which is extremely small compared to other high temperature compatible materials [4].

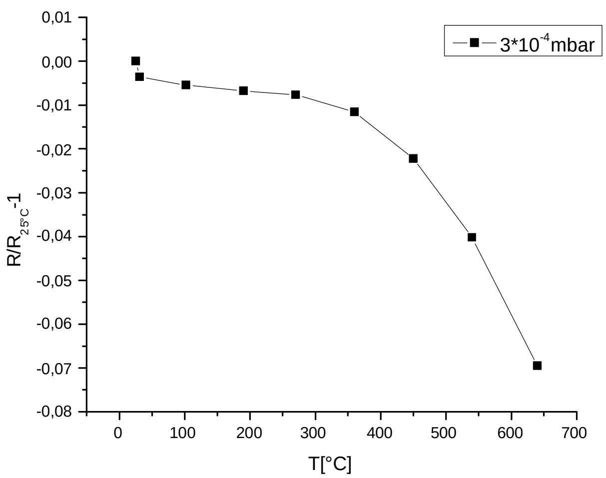

Figure 6: The resistance of SnO_2:Sb thin films exhibits a low impact on temperature.

At maximum membrane deflection the sensor shows a 2.5% change in resistance as output signal. Compared to conventional metal based strain gauge sensors with a change of 0.1% at the elastic limit, this finding is rather promising.

CONCLUSIONS

The pressure sensor system presented here is designed to withstand the HE in propulsion systems. Using non-conventional semiconductor materials we have successfully demonstrated a sensitive strain gauge with low TCR and high thermal stability. The sensor packaging concept is developed and tested for propulsion systems and can be adopted for other sensing systems. The next step in the development roadmap is the elimination of the spring contacts to improve the vibration resistance of the sensor.

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