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Piezoresistive Pressure Sensor Technology for Hydrogen Applications at High Temperatures

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Summary:

We report on a piezoresistive pressure sensor technology suited for pressure measurements in the ranges of 50 up to 1000 bar under 100% hydrogen gas in the emerging hydrogen economy. In contrast to existing solutions, the “dry” technology allows for measurements at elevated temperatures of 200°C and potentially above. The sensor is based on a silicon-on-insulator (SOI) block-type chip technology, with a steel membrane transferring the pressure to the sensing element. The proof-of-concept and stability of the technology could be demonstrated under 100% hydrogen up to 200°C.

Keywords: pressure sensor, hydrogen, high temperature, piezoresistive, SOI

Introduction

In today`s strive towards a future sustainable green energy society, hydrogen (H_2) is expected to play a key role as energy carrier [1]. To technologically and economically enable H_2 applications such as long-haul transportation, a whole “H_2 economy” with the corresponding production and infrastructure needs first to be developed [1]. In this economy, pressure sensors are a key element to monitor and control static and dynamic pressure changes during initial H_2 production, compression to higher pressures, storage, and distribution. Particularly, for the monitoring of static pressures, piezoresistive or thin-film strain gauge sensors are a well-established technology. But when exposed to H_2, technical challenges arise due to the potential embrittlement of H_2-exposed steel parts, as well as H_2 diffusion into the sensor interior [2]. These difficulties make many state-of-the-art static sensor concepts inherently unsuited for the long-term pressure monitoring (> 1yr) of 100% H_2. This is exemplarily shown in Fig. 1(a) for a classical oil-filled piezoresistive sensor, where H_2 can diffuse through the thin steel membrane into the oil filling and cavity of the silicon chip, leading to measurement errors and potential sensor failure [2]. While the sensor lifetime might be somewhat prolonged with additional coatings, the design flaw in the system is inherent. Similarly, standard Ni-Cr metal thin-film strain gauges bonded on a thin steel membrane are very sensitive to interaction with H_2 permeating into the sensor interior [3]. This becomes particularly important for future applications at high temperatures above 150°C, such as H_2 compression or SOFC fuel cells, where diffusion rates are increased. Here, only technologies without transmission fluids (“dry”) and cavity-based Si chips are suitable, and there is a strong need to find fitting high temperature sensor technologies.

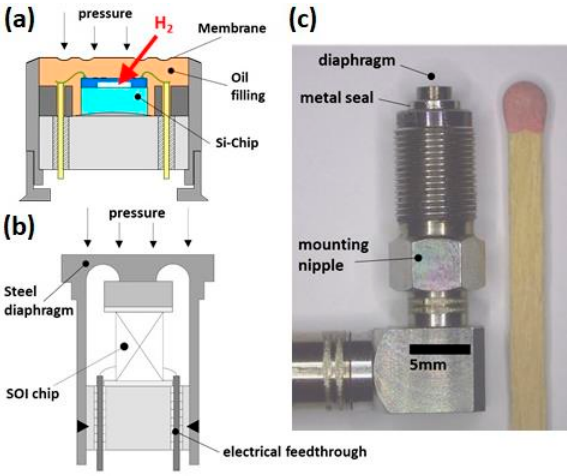

Fig. 1. (a) Typical oil-filled piezoresistive sensor: H_2 can diffuse through the thin membrane into the oil filling and silicon cavity, causing measurement errors. (b) Principle of “dry” block-type piezoresistive sensor technology [4]: pressure is transferred to stress in a SOI block-type chip, measured via piezoresistors on both sides of the chip. (c) Picture of the sensor prototypes, with a 3mm diameter diaphragm.

Sensor concept and testing approach

To allow for measurements under 100% H_2, pressure (p) ranges of 50-1000 bar and temperatures (T) up to 230°C, we use here a “dry” sensor concept [4] schematically shown in Fig. 1(b). Pressure is transferred via a flush-mounted ruggedized steel diaphragm as force on a piezoresistive silicon-on-insulator (SOI)-

based block-type bulk sensing chip. The piezoresistors on both sides of the high temperature capable SOI-chip are sensitive to the longitudinal and transverse strain experienced under load and connected to a full Wheatstone bridge. Depending on the application and p-range, various sensor sizes, membrane thicknesses and front diameters down to 3mm can be realized. For this proof-of-concept study, 14 prototype sensors have been built for a 500 bar p-range, with the design shown in Fig. 1(c). Special care has been taken to use a (flat) metal seal, no welds and only suitable materials in the H_2-exposed parts. Of the 14 prototype sensors, 11 have been tested under 100% H_2 exposure: first with a leakage test at -40°C, 23°C and 200°C, followed by 30’000 p-cycles between 1-500 bar at the respective 3 T’s under recording of the p- and T-signals with an electronic amplifier, and finally all sensors were kept during 1 week at 200°C and 500 bar H_2. For comparison, similar p-cycles were performed under hydraulic oil on the 3 remaining reference sensors. All sensors were calibrated before and after the tests. To rule out any possible failure mechanisms (e.g. in the chip metallization) when H_2 permeates into the sensor, the chip alone (no housing) was also exposed to 100% H_2 at 1 bar and 175°C (to account for the T-gradient). For this purpose, a special setup was built to allow for the live chip signal measurement during H_2 exposure, and to compare the signal drifts with measurements under a neutral Argon gas.

Results

In Fig. 2(a), exemplary results of the chip-level drift characterization over 7 days under 100% H_2 at 175°C are shown. It is visible, that the pure chips drift less or similar in H_2 atmosphere than under the Ar gas reference, all on a small level mostly due to temperature effects. In the total H_2 exposure time of 360h measured at different T’s, no effects due to H_2 could be detected: neither in the 7 live-measured samples nor in particular non-connected samples, that were optically, mechanically and electrically analyzed to rule out any possible failure mechanisms in the chip metallization stack or the chip bond. For the sensor prototypes, leak tightness could be achieved at all tested temperatures according to EC regulation EC79/2009. An exemplary evaluation of 30’000 temperature-stable p-cycles is shown in Fig. 2(b) for the 3 different T`s, showing pressure signal drifts at the lower cycling pressure of ~1 bar (~ZMO) of about 0.1%FSO. This is similar to what could be measured during hydraulic cycling without any H_2 influence. After a total H_2 exposure time of 600h, no influence of the H_2 could be detected and reference sensors behaved similarly, also during (re-)calibration.

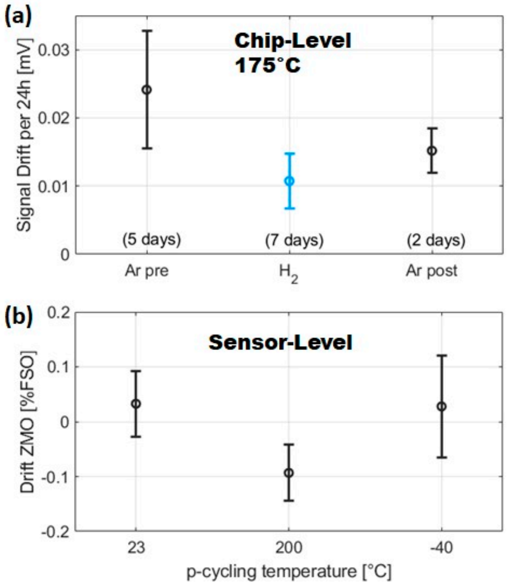

Fig. 2. Drift characterization at chip and sensor level: (a) Normalized and averaged drift signal of 7 chip samples under 100% H_2 compared to their prior and posterior drift under an Ar gas reference at 175°C. (b) Measured and averaged ZMO drift of each 3-4 sensor prototypes during 30’000 p-cycles (about 275h) between 1-500 bar at the indicated T’s.

Conclusion

For the first time, based on a “dry” block-type SOI chip sensor technology, we have shown a technological proof-of-concept for the long-term monitoring of 100% H_2 pressures at 500 bar and elevated temperatures of about 200°C – a limit only due to the current test setup. In contrast to many existing solutions, there is no inherent design flaw such as a liquid filling, and the dry technology has the potential to work even up to 350°C [4]. Based on thorough tests, the sensor technology is expected to provide a robust and reliable solution particularly for future high temperature H_2 pressure measurement applications above 150°C.

References

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