Sensor Systems for Extremely Harsh Environments

Holger Kappert, Fraunhofer IMS, Duisburg, Deutschland, holger.kappert@ims.fraunhofer.de
Sebastian Schopferer, Fraunhofer EMI, Efringen-Kirchen, Deutschland, sebastian.schopferer@emi.fraunhofer.de
Nooshin Saeidi, Fraunhofer ENAS, Dresden, Deutschland, nooshin.saeidi@enas.fraunhofer.de
Steffen Ziesche, Fraunhofer IKTS, Dresden, Deutschland, steffen.ziesche@ims.fraunhofer.de
Alexander Olowinsky, Fraunhofer ILT, Aachen, Deutschland, alexander.olowinsky@ilt.fraunhofer.de
Falk Naumann, Fraunhofer IMWS, Halle, Deutschland, falk.naumann@imws.fraunhofer.de
Martin Jägle, Fraunhofer IPM, Freiburg, Deutschland, martin.jaegle@ipm.fraunhofer.de
Malte Spanier, Fraunhofer IZM, Berlin, Deutschland, holger.kappert@ims.fraunhofer.de

Abstract

Sensors are key elements for the detection of environmental properties and are indispensable in industrial applications for process monitoring and intelligent control of processes. While highly integrated sensor systems are already state-of-the-art in many everyday areas, the situation in an industrial environment is significantly different. The use of sensor systems is often not possible because the extreme environmental conditions of industrial processes such as high operating temperatures or strong mechanical loads do not allow the reliable operation of sensitive electronic components. As part of the Fraunhofer Lighthouse project eHarsh, eight institutes have bundled their competencies and created a technology platform as a basis for the development of sensor systems for extremely harsh environments [1].

1 Introduction

1.1 Motivation

There are various applications demanding for sensors and sensor systems even if these are characterized by extremely harsh environments like e.g. in geothermal energy, oil and gas drilling, stationary turbines or jet engines. Sensor systems are getting indispensable for those applications in the context of industry 4.0 and due to the increasing requirements for safety, clean and energy efficient operation. Thereby sensor systems are not only simple sensing elements, rather they are built of one or more sensing elements, analog electronics for signal conditioning, micro controllers for signal processing and measurement sequencing as well as communication interfaces to specific bus systems or to provide a wireless link (Figure 1). The realization of these highly integrated sensor systems requires various supplementing technologies in order to meet the increasing demand on performance and especially on robustness under consideration of extreme loads such as temperature, pressure or vibration.

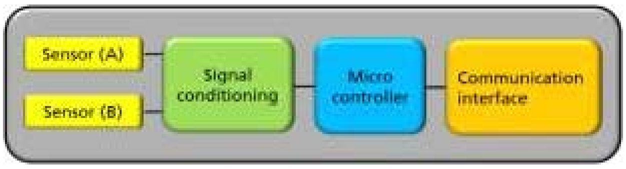

Figure 1 Building blocks of a sensor systems

The necessary technologies were to be identified within the framework of the project and (further) developed accordingly. For that purpose, the participating Fraunhofer institutes were to contribute their specific technologies and application know-how and make them available in an eHarsh technology platform. In particular, the specific requirements from the two selected application fields of turbines and geothermal energy were to be considered.

1.2 Project structure

A consortium of eight Fraunhofer institutes i.e. Fraunhofer institutes for High-Speed Dynamics EMI, Electronic Nano Systems ENAS, Ceramic Technologies and Systems IKTS, Laser Technology ILT, Microelectronic Circuits and Systems IMS, Microstructure of Materials and Systems IMWS, Physical Measurement Techniques IPM, and Reliability and Microintegration IZM was specifically assembled for the various aspects of sensor system development. Both for the functional elements such as sensors and electronics and for their assembly and interconnection the underlying technologies have been developed. In addition, aspects like material characterization as well as simulations and modeling for reliability were investigated. In three work packages, the technology platform and two dedicated demonstrators have been developed, respectively. One demonstrator has been related to the application field turbines and the other one has addressed the requirements of geothermal applications.

2 Technology platform eHarsh

In the course of the project several technologies have been investigated. Even if some of these technologies like sensors or electronics have already been shown to be operable at high temperatures, complete sensor systems are still challenging with respect to the level of integration, system assembly and finally their reliability. Therefore, special focus has been on the interoperability of the different tech-

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nologies and on the reliability with respect to the requirements of the extremely harsh environments. Here especially the conditions of the selected applications turbine and geothermal energy have been considered. The following technologies have been investigated in detail:

2.1 Sensors

Various sensors have been analyzed. Special focus has been on ceramic based sensors and micro-electro-mechanical systems (MEMS) based sensors. To address temperatures up to 500 °C at the sensor element ceramic based sensors, i.e. pressure and temperature sensors have been investigated [2]. To achieve reliable and performant sensors for a wide temperature range up to 500 °C new pressure and temperature sensitive materials have been developed. For applications in the field of deep drilling capacitive micromachined ultrasonic transducers (CMUT) have been investigated [3]. Starting from an existing design, the CMUT elements have been improved for higher ultrasonic pressure and a protective housing has been developed which allows the use of the sensor in harsh environments. The transducer was tested for different conditions including immersed in drilling mud or at high temperature (200°C). A measurement range of up to 5 cm has been demonstrated in drilling mud.

2.2 Electronics

Besides the sensor, electronic components are necessary for signal conditioning, processing and communication to the overall measurement or control system. Based on the Fraunhofer IMS high temperature silicon-on-insulator complementary metal oxide semiconductor (SOI-CMOS) technology a dedicated sensor electronic more precisely a chipset of three chips has been developed for operation up to 300 °C [4]. The chipset comprises a sensor frontend chip, a microcontroller and a power supply chip. The analog frontend chip includes three signal paths each equipped with an offset compensated instrumentational amplifier and a sigma-delta analog to digital converter. The microcontroller includes a 32-bit core based on the RISC-V instruction set and several standard peripherals like GPIO, SPI, UART and timer. The power supply chip provides the internal supply voltages of the system and a physical RS485 interface which enables a robust communication over a sensor bus.

2.3 Assembly technologies

The assembly technologies used to mechanically and electrically connect the various components are important for the system integration and are key elements for reliable operation. In the course of the project specific technologies have been investigated. For the assembly of the chips and the passive components on the ceramic boards, silver sintering has been applied. A new technology allows flip-chip bonding of the chips to the ceramic also for high temperature applications. Therefore, fine pitch silver sintering has been investigated.

Besides the ceramic based assembly embedding technology even for high temperature applications have been introduced. In combination with a board-level housing using electro plating a fully hermetically encapsulated electronic at minimal size has been realized. This technology is especially interesting for applications in humid environment.

2.4 Joining technologies

For the next level of system assembly especially for the realization of the sensor encapsulation various laser based joining technologies have been investigated. Specific to the different interfaces like metal-metal or metal-ceramic dedicated technologies have been selected and optimized according to the system requirements.

2.5 Material characterization and damage analysis

Parallel to the development of the different technologies sketched above, various materials have been characterized for usage under extended operation conditions and to extract parameters for accompanying reliability simulations. Established characterization methods have been improved to extract material properties at elevated temperature up to 500 °C [5].

2.6 Reliability and modeling methods

The development of the different technologies has been supported by several simulations. Simulation models have been continuously refined based on the material characterization and the analysis of damage patterns and have allowed comprehensive reliability simulations. The simulation results have been the basis for further optimization of processing steps, material selection or geometries.

2.7 Test rigs

The development of sensor systems for extremely harsh environments finally also requires the test and characterization of the sensor systems close to the application. For this purpose, specific test rigs have been developed. For the turbine demonstrator a dedicated test rig has been realized supporting combined thermal and mechanical load. In addition, a shock tube has been constructed for characterization of the sensor regarding high dynamic pressure changes.

For the test under geothermal conditions a borehole emulator has been developed based on a cylindric pressure chamber. The chamber has been equipped with electric feedthroughs for monitoring and characterization at high pressure and temperature in water (alternatively oil).

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3 Demonstrators

3.1 Turbine sensor

A complete pressure sensor (Figure 2) has been realized for the turbine application field. The ceramic pressure and temperature sensor elements allow measurements at ambient temperatures of up to 500 °C at the tip of the sensor. The integrated chip set allows signal processing at temperatures of up to 300 °C inside the sensor housing. Silver sintering was used for the assembly and connection technology. The used joining technologies provide a very good Helium tightness of the sensor encapsulation.

Figure 2: Turbine pressure sensor

The sensor has been finally characterized using the dedicated test rigs. To facilitate transfer to industry, simplified demo boards have been produced and can be made available for customer evaluation.

3.2 Geothermal energy

For the application in field of geothermal energy, hermetically encapsulated modules based on the enhanced embedding technology have been realized (Figure 3). The performance has been analyzed with different modules with the high temperature ASICs embedded inside the board. Besides the embedded components ceramic elements have been laminated together with the printed circuit board supporting electrical connection or carrying sensor elements like for pressure or temperature. The modules have finally been characterized in the borehole emulator.

4 Conclusion

A comprehensive technology platform for the realization of sensor systems for extremely harsh environments has been developed in the framework of the Fraunhofer Lighthouse project eHarsh. Several key technologies like sensors, electronics, assembly and joining technologies have been identified and improved or developed accompanied by material characterization and reliability simulations for use in harsh environments, respectively. The performance of this platform has been successfully evaluated based on selected demonstrators in the fields of turbines and geothermal applications.

Figure 3: Hermetically encapsulated modules

5 Literature

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