Acceleration Sensors IP-Blocks for MEMS Foundry Surface Micromachining Process

R. Knechtel, S. Dempwolf
S. Hering
X-FAB Semiconductor
Foundries AG
Haarberstraße 67
99097 Erfurt / Germany

T. Link
MicroMountains
Application AG
Romäusring4
78050 VS-Villingen

J. Dehnert , D. Hoffmann,
M. Trächtler
HSG-IMIT
Villingen-Schwenningen
W.-Schickard-Str. 10
78052 Villingen-Schwenningen

Abstract

In this paper, micromachined acceleration sensors as ready-to-use Intellectual-Property-Blocks (IP-Blocks) are introduced. These standard elements are available for a special surface micromachining foundry technology. They are ready to use, characterized and qualified design elements, which can be customized by changing the peripheral elements such as bond pads, and allow a fast prototyping and production start of high-performance inertial sensors.

Introduction

Using silicon-based MEMS technologies, the cost-efficient production of inertial sensors has become possible in recent years. Furthermore, ready-to-use MEMS foundry technologies allow both the manufacturing of high volumes and small series. Since the technology is developed and provided by a MEMS foundry, the main challenge for bringing an inertial sensor to the market is the chip design, for which MEMS design experience is required. In order to give customer support at this point, IP (Intellectual Property) design blocks for acceleration sensors were developed, processed and characterized. These allow customer-specific modification (e.g. for pad layouts), and are ready to implement in specific solutions.

Surface Micromachining Technology

Firstly, the MEMS foundry technology, meaning the universally-usable manufacturing process for inertial sensors, in which the acceleration sensor IP blocks are manufactured, is introduced. In addition to the acceleration sensors, other inertial sensors such as high-performance gyroscopes or inclination sensors can be produced with this process. Figure 1 gives an overview of the final chip structures in which movable mechanical elements, such as seismic masses, springs and read out capacitors, are realized, electrically contacted and hermetically sealed by silicon caps.

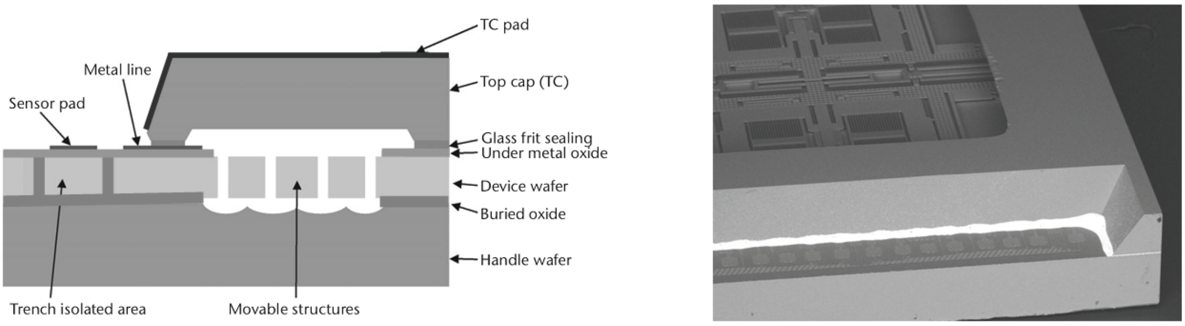
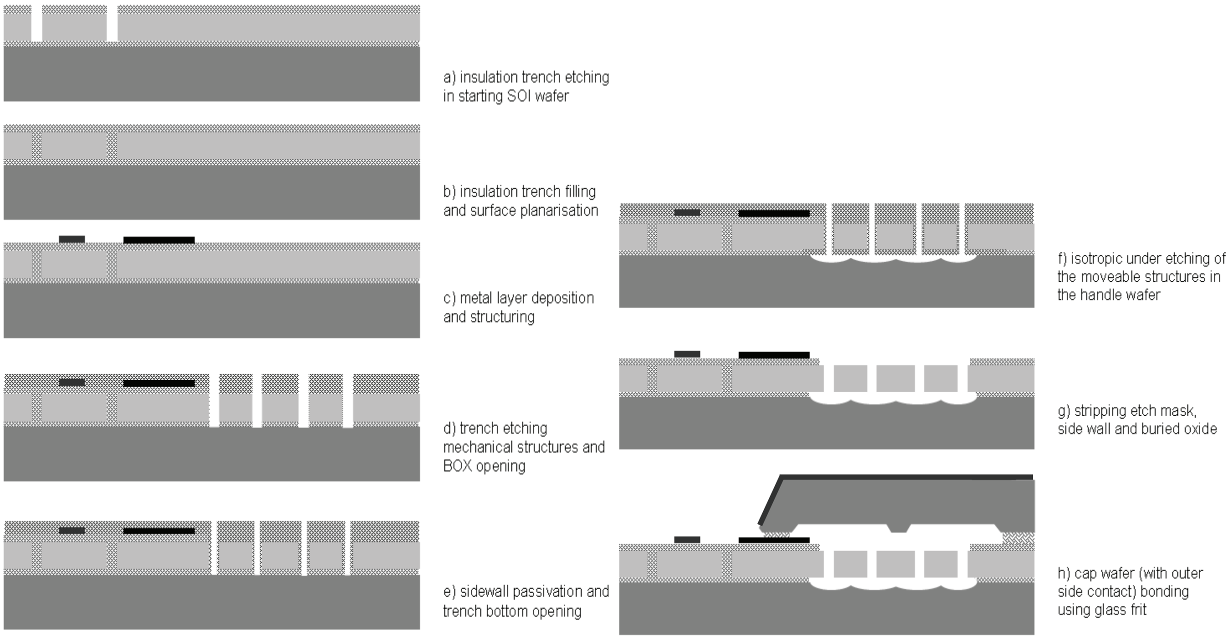


Fig. 1: Cross-sectional principle of the surface micromachining process and its realization with an opened cap

The technology is based on an SOI wafer, which is a special substrate providing many technological benefits, despite being cost-intensive. The main advantage is that the moveable structures are made from a single crystalline device layer of 15µm, and hence have excellent, well-defined mechanical properties and high reliability. For realisation of the complex mechanical inertial sensor structures (seismic mass, comb drives, read-out capacitors), trenches and holes are etched anisotropically in the device layer of the SOI wafer, down to the buried oxide, retaining the shape of the inertial sensor mechanics. To release the mechanical structures, the sidewalls of the etched silicon structures are passivated with CVD oxide, and the buried oxide is opened at the bottom of the trenches. By using isotropic etching into the silicon handle wafer, then the structures are under-etched and their ends released. In this process, the width of the structure defines whether a structure becomes moveable or remains fixed. Subsequently, any remaining oxide is stripped from the mechanical structures by HF vapour etching, so that only pure single crystalline silicon remains. To improve the electrical behaviour of the inertial sensors, filled insulation trenches are processed prior to the fabrication of the mechanical structures. These trenches separate the structure as well as the bond pads from the surrounding chip and allow defined electrical contacting of the different sensor elements by metal wiring. However, the main benefit of the trenches is the reduction of parasitic capacitances, which greatly increases the mems inertial sensor performance. Furthermore, an insulation layer between the silicon device layer and the metal layer in the area surrounding the mechanical structures provides the possibility of complex electrical wiring around the mechanical structure. Finally, the mechanical structures are sealed with a capping wafer using glass frit wafer bonding [1]. The capping wafer is pre-structured with through-holes to reach the bond pads after bonding, as well as cavities over the sensor structures This bonding provides effective protection of the very sensitive mechanical structures at the wafer level, making standard wafer probing, dicing and assembly processes possible. Due to the planishing effect of the soft glass frit during bonding, metal lines for driving and sensing signals can be embedded in the glass, and by this, hermetically sealed, so that. Because capacitive sensor elements, which typically provide low signals, are generally EMC sensitive, the back and front sides of the bonded wafer stack are metallized to enable effective shielding by connecting the cap and base to ground. Figure 2 shows the general process flow of the surface micromachining foundry technology for acceleration sensors and other inertial sensors.



a) insulation trench etching in starting SOI wafer

b) insulation trench filling and surface planarisation

c) metal layer deposition and structuring

d) trench etching mechanical structures and BOX opening

e) sidewall passivation and trench bottom opening

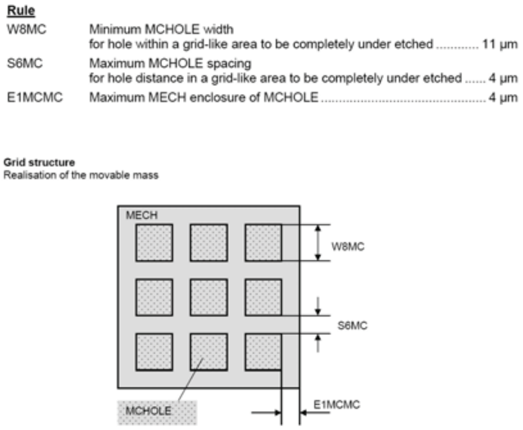
f) isotropic under etching of the moveable structures in the handle wafer

g) stripping etch mask, side wall and buried oxide

h) cap wafer (with outer side contact) bonding using glass frit

Fig. 2: Principle process flow of surface micromachining based on SOI wafers, using deep silicon trench etching for mechanical structures in the SOI wafer, isotropic silicon release etching in the handle wafer, and glass frit bonding for hermetic encapsulation

The MEMS Foundry Technology is ready-to-use, and is described by process- [2] and design rule [3] specifications. The process specification contains all wafer process-related information required in the design process and for assembly. The main process flow, including sensor and capping wafers as well as the bonding and in addition the wire bond pad configuration is described,. Special tables provide data on the starting SOI wafer, layer thicknesses, operating conditions (voltages, current densities), process control parameters, and structural/geometrical, electrical and parasitic parameters. The design rule manual defines all process layers, describes the rules for these layers through minimum widths such as for the mechanical structures, or fixed widths as for the insulation trenches, and minimum spacings, such as for the metal lead-through ducts under the glass frit. In addition, the relationships of the process layers to each other are defined by enclosure, extension overlap and spacing rules. An example is given in Figure 3 for the seismic mass, which must be realized as a grid-like structure with certain dimensions to enable complete underetching in the release etching step. In order to build up a capacitive inertial sensor design (for example for the manufacture of a gyroscope) special design elements such as combs, anchors, anchored silicon, contacts, lines, fixed-to-move transition elements (to contact the moveable structures) or wire crossings (by using the silicon device layer and insulation layer in a single metal layer technology) are required in each case. These elements are also part of the design rule specification and shown as an example in Figure 4. They are described as device rules under consideration of the technological aspects of such special geometric configurations. As an example, the comb drive element will be introduced here. By use of these types of device rule, complex structures are given to the MEMS designers to achieve a fast design process, but by providing ranges of design measures (e.g. 2-6 µm moveable finger width) and additional rules linked to these by calculation formulae, design flexibility is guaranteed.



Rule		
W8MC	Minimum MCHOLE width for hole within a grid-like area to be completely under etched	11 µm
S6MC	Maximum MCHOLE spacing for hole distance in a grid-like area to be completely under etched	4 µm
E1MCMC	Maximum MECH enclosure of MCHOLE	4 µm

Grid structure
Realisation of the movable mass

Fig. 3: Design rule example for moveable seismic masses

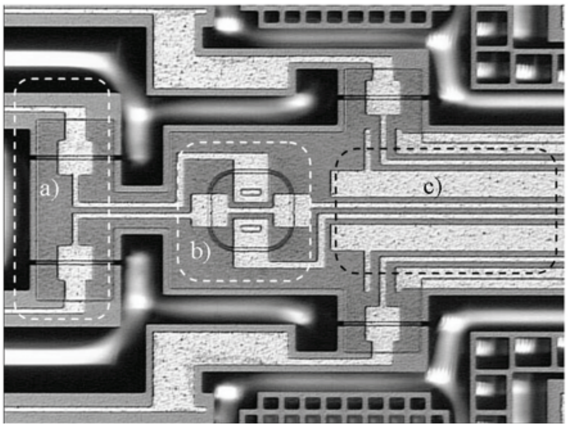


Fig. 4: Design elements, such as fixed-to-move transition (a), wire crossings (b) and shielding lines (c)

Even if the surface micromachining process is, in principle, layer-related and the 3D character of the resulting MEMS structure is mostly defined by the device layer thickness and isotropic under-etching, very complex geometries are typical, which cannot be completely controlled in a layer-based design process. Therefore in addition to special design rule check, the surface micromachining process was modelled using a process simulation tool (Coventor, Inc., SEMulator3D^{TM} [4]), which enables the conversion of a GDSII design file into a 3D model to check critical design elements and to optimize these for manufacturing. The tool creates highly realistic 3-D virtual prototypes of micro-fabricated devices. Examination of these virtual prototypes can reveal design errors as well as the impact of design changes and process variations before each mask tape-out and fab run, potentially reducing or eliminating design-fabrication-test cycles.

Even if the technology is very well described and explained to MEMS designers by the design and process specification documents, it is still very difficult and critical to design new inertial sensors with specific well-defined and predictable measurement behavior. This ultimately was the motivation to develop completely analyzed and characterized acceleration sensor IP blocks, which can fulfill all design rules to allow both fast prototyping and safe, stable mass production later on.

IP-Block Design and FEM Simulation

The market and application analysis has shown that there are needs for acceleration sensors in different measurement ranges: high-precision low-g-Sensors for the high-end market segment, high g-Sensors which are less sensitive but low-cost, and medium range sensors. IP blocks for these sensor elements were designed, related to the X-FAB MEMS foundry technology for surface micromachined inertial sensors. Here initially, the basic mechanical design was defined by Matlab calculations based on the physical principle of a mass-spring-damper system with capacitive read-out of the acceleration initiated seismic mass movement. This means the size of the seismic mass, the spring configuration and the number and configuration of the read-out capacitors were fixed. All of these elements are crucial for the sensor function, which applies for the sensitivity but also for boundary parameters such as shock overload robustness and frequency behavior. In this design phase FEM was very important to meet all the requirements of the mechanical behaviour (resonance frequency, bandwidth, damping, linearity, mechanical shock) and of the final electrical function (base capacity, capacity change related to measurement signal). Figure 5 shows the modal FEM results of the first 4 modes of the 100G sensor as an example. In Figure 6, the FEM calculations regarding shock overload are shown.

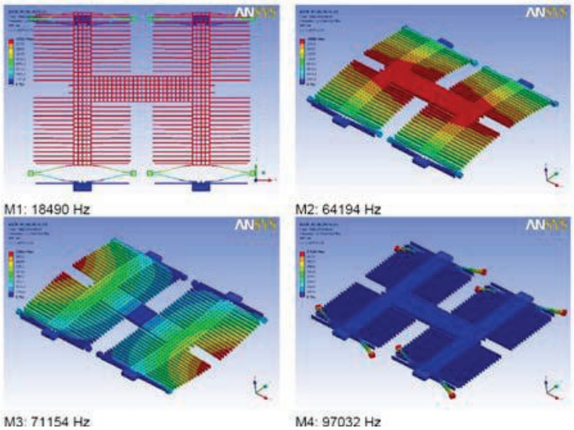


Fig. 5: Modal Analysis of the 100G Acceleration Sensor

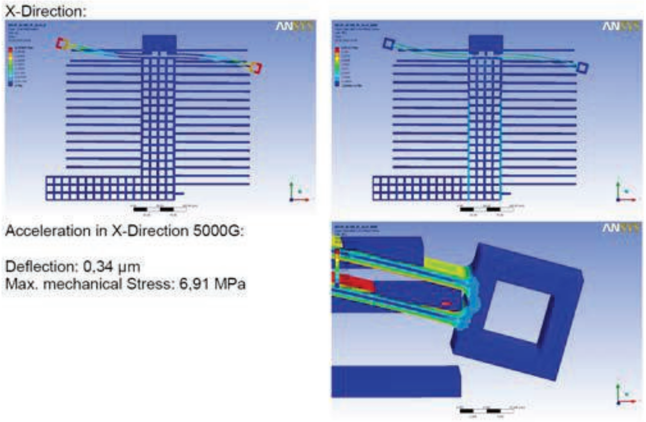


Fig. 6: FEM-simulation of 5000G shock overload robustness

Based on these calculations and simulations, the layout of 3 acceleration sensor IP blocks was performed. These three sensors of 2G, 10G and 100G maximum measurement range (G earth gravitation constant) cover the whole range of potential applications from input devices and mobile devices up to automotive applications. Figure 7 gives an overview of the three layouts and their target parameters. In this figure the designs are not to scale, in order to show both an overview and details.

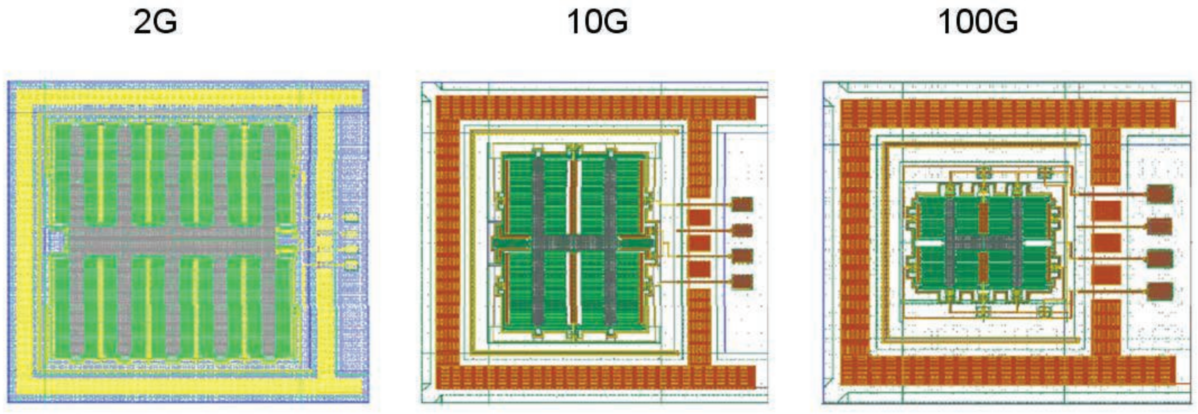


Fig. 7: Overview of acceleration sensor IP block layouts

Realization and Characterization

After assuring the complete fulfilling of the design rules and 3D-Design check using the SEMulator3D^{TM}, the IP blocks are processed in the MEMS foundry technology based on SOI-Wafers. The mechanical structures are etched out of single crystalline silicon and as a result, have excellent mechanical properties. Since the mechanics are capped at the wafer level, the chips can be mounted in open standard packages and characterized using standard signal conditioning electronics, see Figure 8. In the assembly of the sensor devices, a special PCB rewiring was used to obtain the best conditions for the small capacitive signals. Additionally, a silicon interposer chip was placed between the standard package and the sensor chip to prevent any influence of packaging stress. As signal conditioning for the characterization, the Analog Devices Evaluation Board of the capacitive sensor interface AD7746 was used [5], since this is also available to any final customer for evaluation testing. In the final application, this electronics is intended to be replaced by an ASIC solution,.

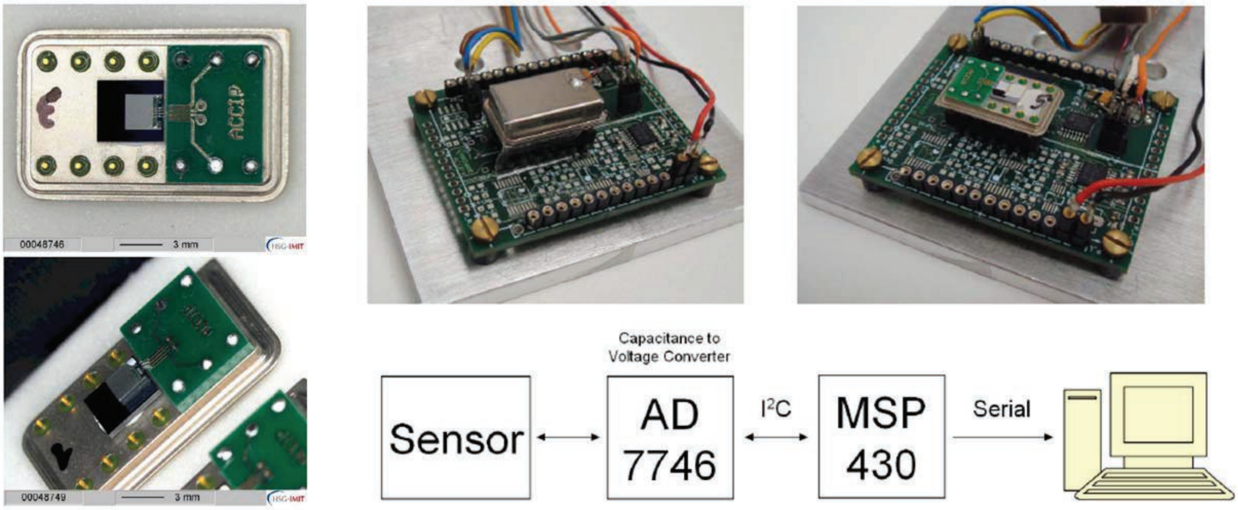


Fig. 8: Package and setup for characterization

The mechanical acceleration movements to characterize the sensor chips were provided by a 3-axis-turntable and a shaker system. The characterization, which was done at different temperatures, shows very good acceleration sensor behaviour, all targets defined in the design phase were achieved with these IP-Block samples. Figure 9 shows some characterization results for the +/-1g measurements.

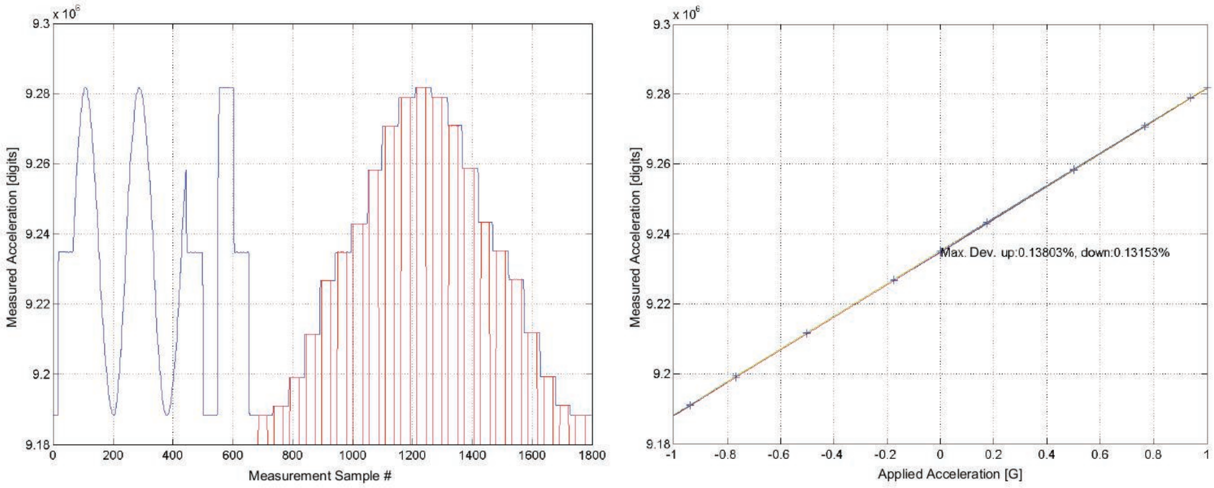


Fig. 9: Examples of Characterization Results of 2G-Sensor at different angles to earth gravity

Conclusions

By providing IP blocks for 2, 10 and 100 g Acceleration Sensors in a well-established MEMS foundry technology, a following step in MEMS standardization is done, which simplifies the use of customized MEMS inertial sensors. These acceleration sensor IP blocks are well characterized (a summery of the characterization data is shown in Table 1), and qualified for automotive requirements. Hence, they are ready to use for prototyping and mass production for different fields of application such as automotive, medical or customer devices.

> Typical characteristics (typ. values)				
Parameter	2g-Sensor	10g-Sensor	100g-Sensor	Unit
Measurement Range	± 2	± 10	± 100	g
Temperature Range	-40 ... +125	-40 ... +125	-40 ... +125	°C
Base Capacitance (one electrode)	10.0	2.0	0.65	pF
Sensitivity (Change of capacitance)	22.0	3.2	0.27	fF/g
Resonance frequency	8	10	18	kHz
Noise Density	0.25	1.0	12.0	mg/sqrt(Hz)
Non-Linearity	0.02	0.03	0.30	% FSO
Bandwidth	> 500	> 1500	> 3000	Hz
Shock Survival	> 1000	> 3000	> 5000	g
Total Size of Die	4.5 x 4.0	2.7 x 2.5	2.3 x 2.0	mm^2

Table 1: Measurement characteristics of acceleration sensor IP blocks

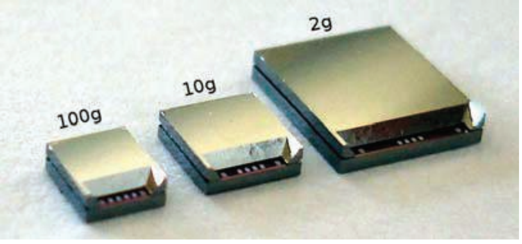


Fig. 10: Acceleration sensor IP-block chips

Acknowledgements

The authors would like to thank the German Ministry for Education and Research for funding the research and development part of this project organised by the Application Center for Microsystems Technology „MicroMountains Applications".

Refernces:

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