RESEARCH EXAMPLES AND DEVELOPMENT OF SURFACE MICROMACHINING PROCESS USING POROUS SI AS SACRIFICIAL LAYER

Ulrich Mescheder
University of Applied Sciences in Furtwangen,Germany
umescheder@ffurtwangen.de

Perrin Smith Neto
Pontificial Catholic University of Minas Gerais- Brazil
psmith@pucminas.br

Abstract. This paper presents research examples in the field of micro-technology developed in the Microtechnology Laboratory of the University of Appplied Sciences in Furtwangen , Germany. It shows also development of a kind of surface micromachining process using porous Silicon as sacrificial layer. The authors describe different types of microphones that have been developed in a process combining surface and bulk micromachining. Different packages have been investigated to enhance the performance of microphones. Another interesting application is the development of a surface micromachined absolute pressure sensor for a tire-pressure sensing system. Finally it describes a design of a bulk micromachined two axes tilt sensor.

Keywords. *Microtechnology , microsensors, tilt sensor, Micromachining process*

1. Introduction

Sensors are devices that provide an interface between electronic equipment and the physical world. They help electronics to “see”, “hear”, smell”, “taste”, and “touch”. In their interface with the real world, sensors typically convert non-electrical physical or chemical quantities into electrical signals. Microsensors have become an essential element of process control and analytical measurements systems, finding countless applications in, for example, industrial monitoring, factory automation, the automotive industry, transportation, telecommunications, computers and robotics, environmental monitoring, health care, and agriculture- in other words in almost all spheres of our life. The main driving force behind this progress is the prize reduction factor achieved by high volume production techniques deduced from microelectronics. Further on, the evolution in the signal processing has supported this progress. With the development of microprocessors and application specific integrated circuits, signal processing has become cheap, accurate, and reliable. On the other hand, a micro actuator is a miniaturized device which converts electrical signals (energy) into a non electrical output (energy). Examples of such microactuators are movable micro mirrors, micro motors, linear drives or inkjet heads. In many cases, electrostatic principles are used for actuation. However, other actuation principles such as piezoelectric or thermal are also explored. The sensor industry has grown rapidly in recent years. The marked share is rather evenly divided between the United States, Japan, and Europe. The rest of the World has about 14% of the world sensor marked. This paper presents research examples in the field of micro-technology developed in the Microtechnology Laboratory of the University of Applied Sciences in Furtwangen , Germany. Main research topics are physical microsensors and process development in the field of microtechnology:Microphone, absolute pressure sensor, tilt sensor, porous silicon technology. In the first two examples miniaturisation is an important issue not only due to the corresponding price reduction effect which comes along with miniaturisation but is needed in the specific application, too. Besides the device fabrication itself the integration of MEMS into the macro world is one of great challenges in MEMS technology. The first step of this integration is in many cases the bonding of the silicon wafer including the MEMS and in many cases the microelectronic devices (monolithical integration) to a cap or bottom wafer which might provide additional functions to the final device or may only serve as protection of the fragile MEMS device. There are a number of different methods available for bonding micromachined silicon wafers together, or to other substrates, to form larger more complex devices. A method of bonding silicon to glass that appears to be gaining in popularity is anodic bonding (electrostatic bonding). The silicon wafer and glass substrate are brought together and heated to temperatures up to 400°C. In a first step, a large electric field (typical voltage 500 V) is applied across the join will form a depletion zone at the interface due to the movement of ions out of the glass away from the interfaces, which causes an extremely large electrical field at the depletion zone and thus a large Electro static pressure (about 10 bar). Under this large pressure a strong chemical bond is form between the two materials. Figure 1 shows a set-up of a anodic bonding apparatus.

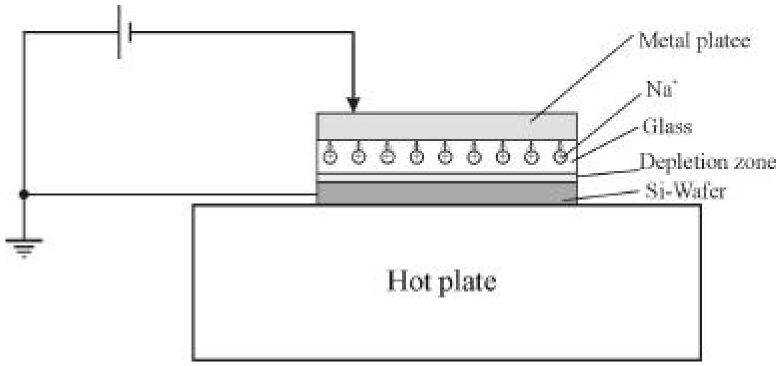
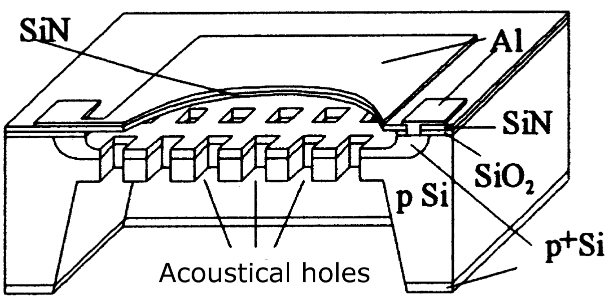


Figure 1 Anodic bonding set-up

It is also possible to bond silicon wafers directly together using gentle pressure and elevated temperatures (direct silicon bonding). Using thin films of Au or Al between the bond partners (at least one of them Si) an eutectic bond can be formed due to the low melting point of the Au-Si and Al-Si alloys. Other bonding methods include using an adhesive layer, such as a glass, or photoresist. Whilst anodic bonding and direct silicon bonding form very strong joins they suffer from some disadvantages, including the requirement that the surfaces to be joined are very flat and clean. A new type of bonding is the local laser bonding technique (Mescheder, Aachen). Using a suitable laser wavelength a transparent substrate (Pyrex for Nd:YAG laser or Si for a CO_2-laser) can be bonded to a Si-wafer containing the MEMS-systems. The temperature stress is limited to the bond area only. Thus, even very sensitive devices are not damaged. Additionally, electrical connection can be provided through the bond pads using standard metalisation such as Al (U. Mescheder, M. Alavi; K. Hiltmann; Ch. Lizeau, Ch. Nachtigall and H. Sandmaier).Wafer bonding techniques can potentially be combined with some of the basic micromachined structures to form the valves, pumps, etc, of a microfluid handling system.

2. Miniaturised microphones

Miniaturised microphone can be used as hearing aids and need to be small to fit into the auditory channel of the ear. Different types of microphones have been developed at the University of Applied Sciences in Furtwangen (E.Graf,1992; W.Kronast,2001). In Fig. 2a a schematic set-up of a microphone realised in a process combining surface and bulk micromachining is shown. Whereas bulk micromachining is used for etching of a backside access of the acoustic wave and the acoustical holes in a rigid backplate, a special type of surface micromachining is employed for the definition of a very thin gap between the back plate and the Al-covered SiN-diaphragm which provides high sensitivity for the capacitive sensing. Fig. 2b shows a photograph of two square membranes of an array of such microphones. In Fig. 2c a close up of microphone with a polysilicon membrane including first pre-amplification electronics is shown. As for many other Microsystems also in the case of microphones packaging is a crucial tropic. Different packages have been investigated to enhance the performance of microphones by special packages. One of the most promising approaches is the principle of the so called slot microphone (A.Stoffel,1998;A.Kovacs,2000). A completed packaged slot microphone is shown in Fig.2d.



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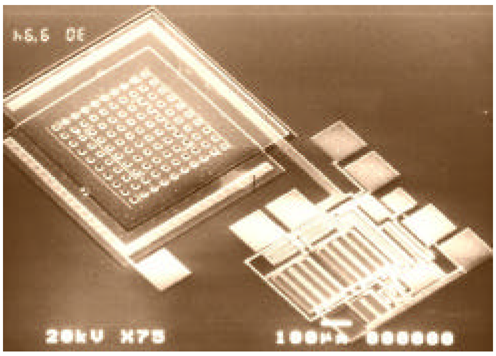

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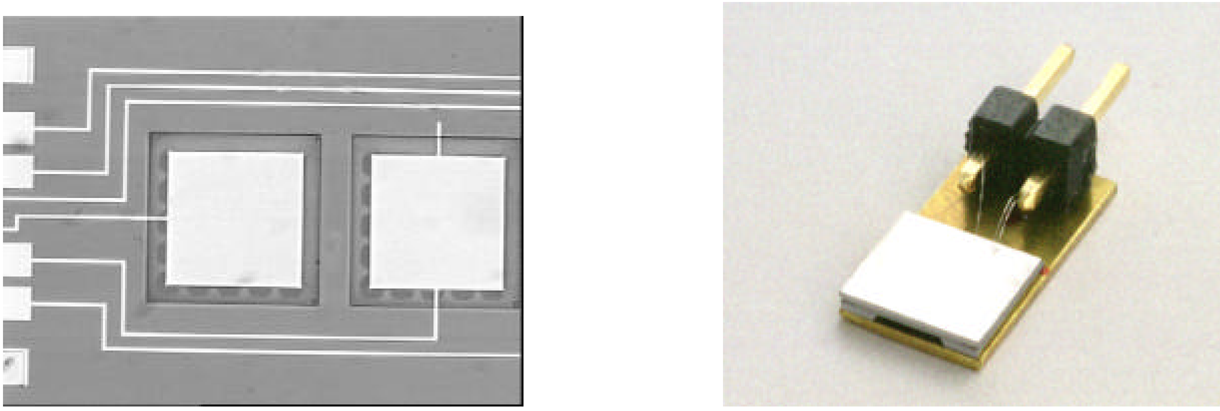


c **d**

Figure 2: Miniaturised microphones realised at the University of Applied Sciences

3. Surface micomachined pressure sensors

Another interesting application is the development of a surface micromachined absolute pressure sensor for a tire-pressure sensing system. Measuring the tire pressure is one actual demand in the automotive industry due to increasing safety requirements. In a research project together with the University of Applied Sciences in Offenburg, Germany, a concept has been investigated for the realization of a pressure and temperature sensing within the tire. In this approach a very small chip including temperature and pressure sensor and the electronic circuit is vulcanized into the rubber of the tire. Energy supply of electronics and sensors as well as data transfer to the outer vehicle bus-system are provided by inductively coupling through a coil and a transponder, both attached to the tire and the circuit. Fig. 3 shows the concept (top) and some details of the pressure sensor. The absolute pressure sensor was realized by surface micromachining using sputtered oxide as sacrificial layer and poly-Si as diaphragm. For sealing a double layer process is used which seals the etch channel which are provided from the side to the membrane. Using a cell type structure the sensitivity and the total capacitance of the pressure sensor can be adjusted. The pressure sensitive capacitance change is measured using a bridge type configuration with a non pressure dependent reference capacitance.

4. Porous Silicon as multifunctional material for MEMS application

One challenge of technology development for MEMS is the demand of keeping process a simple as possible even for multifunctional devices. The main reason for this demand are costs and reliability issues. Many solutions developed in research laboratories throughout the world suffer from the fact that the demonstrated performance could be achieved by sophisticated processes only. However, for successful transfer to an industrial application processes needed for the realisation of multifunctional MEMS or Microsystems should be as simple as possible. Porous silicon is formed out of a crystalline substrate by an anodization process in HF/ethanol/water mixture. Thus porous Silicon consists of a skeleton (c-Is) and voids (pores). Pore size and porosity are determining most of the material properties and can be adjusted by the anodization process (typical porosity is about 60 %, pore size ranges from a few nm to several tens of nm. The most interesting properties of porous Silicon are: high solubility in weak acids and alkaline solutions, Electro- and photoluminescence, high inner surface, adjustable Young's modulus, refractive index, band gap and low thermal conductivity. Therefore, porous Si can be used in optoelectronics, micromachining and sensor and actor applications. We have developed a new kind of surface micromachining process using porous Si as sacrificial layer. Instead of standard surface micromachining where the functional materials are made out of polycrystalline materials such as poly-Si and Si_3N_4 in our process free-standing functional layers out of crystalline Si are formed. The thickness of the c-Si is controlled by the doping concentration of n-Si which is stable during anodization whereas p-Si is transformed to porous Si which is finally removed in weak KOH. Fig. 3 shows one possibility to adjust the needed thickness of the free-standing c-Si structures by the depth of the pn-junction. Another possibility is to change the doping concentration level at the surface while keeping the junction depth constant (U.Mescheder,2001). Fig. 3 shows the principle of this surface micromachining process, the thickness control by the depth of the pn-junction and some freestanding c-Si structures fabricated by this process.

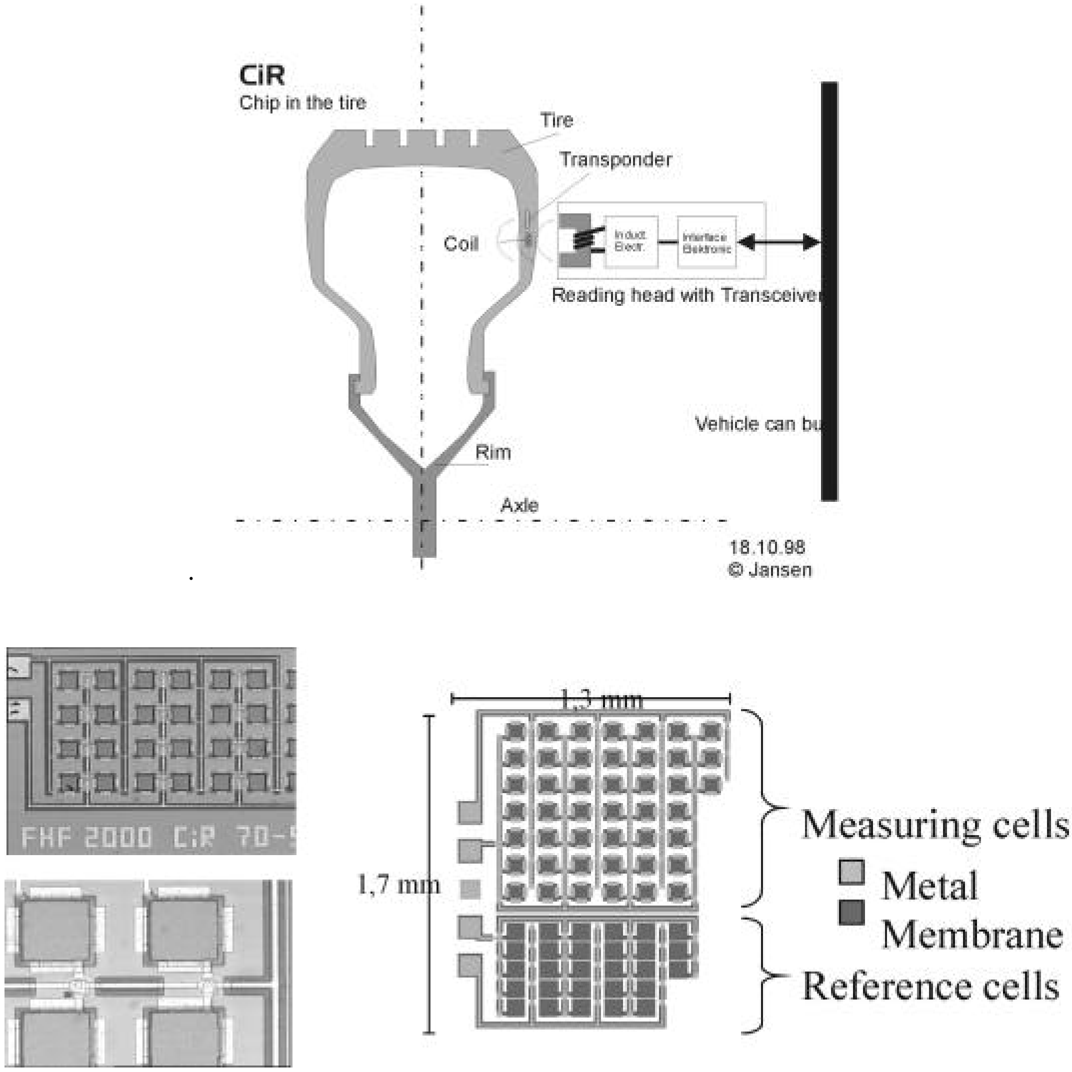
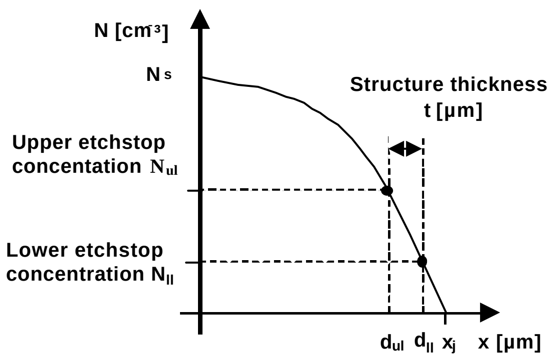
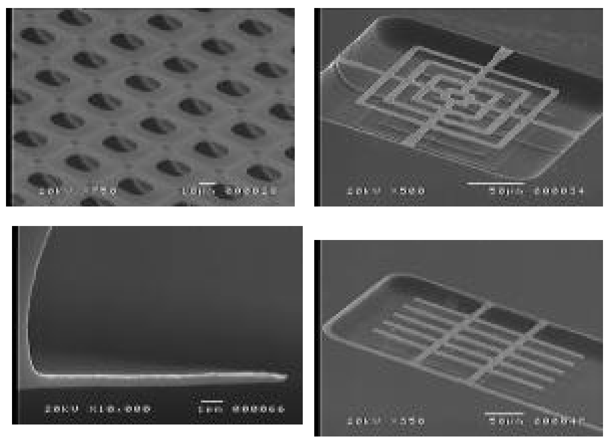


Figure 3: Tire pressure measuring system. Top: system concept, bottom: layout of the sensor chip (right) and some microscope images of the fabricated device (left).





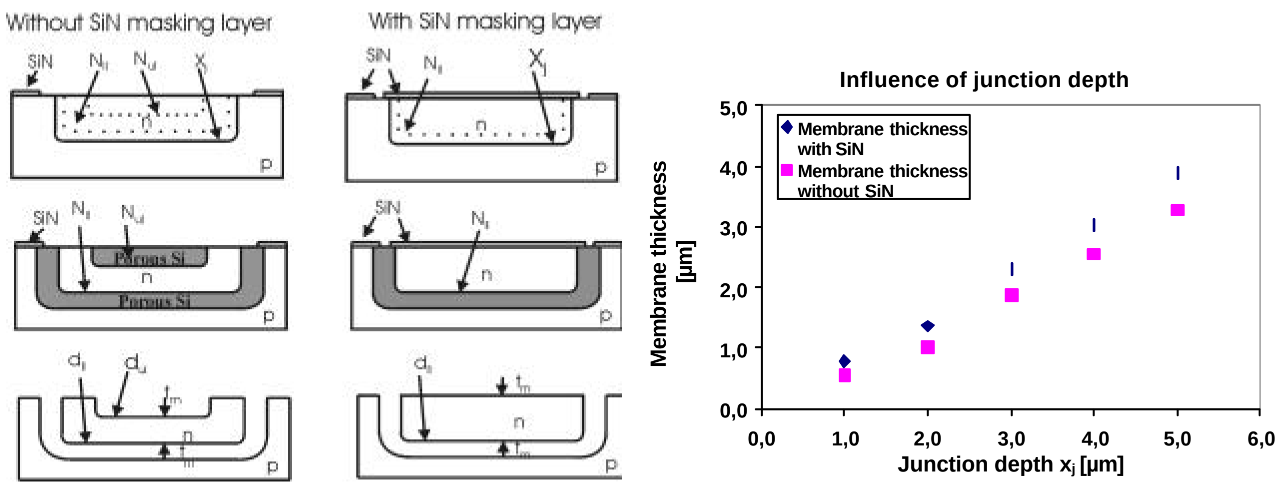


Figure 4: New kind of surface micromachining using porous silicon as sacrificial layer. Free-standing crystalline structures are formed out of n-Si by underetching the n-tub because p-Si is anodised (top left). n-Si is only stable within certain doping concentrations (top right), thus allowing a precise control of the thickness of the remaining n-doped structures (lower left). Even fragile structures with sub-micrometer thickness can be formed (lower right).

Porous Si can be also used as active layer. Due to its high inner surface it can take up easily many gases and humidity. Therefore, porous Si can be used as sensing material. The sensor consist of porous Si in which suitable comb-like electrodes are forming a capacitance which is changing in response to a load with humidity. The sensor contains also heater elements to refresh the sensor. Heating elements embedded in the porous Si are reducing the power consumption of a refresh (at typically > 80°C).Several different realisation concepts have been tested. Especially reliable contact to porous Si is an issue which has to be carefully controlled. Fig. 4 shows the sensor (top left), a cross-section through two types of contact schemes (both electrodes in porous Si one electrode in porous Si one on the c-Si substrate) (upper right) and the performance of the sensor (lower two diagrams).

5. Tilt sensor

An inclination (tilt) is an important magnitude in several automotive applications such as load dependent regulation of automatic gears, chassis regulation and overall detection. Other application areas are hand hold optical instruments, electronic water-levels and substitution of mercury switches. Future applications might be also in the medical field (cardiac pacemakers, computer assisted operation). For these applications miniaturized low cost sensors working even under harsh environmental conditions are needed. Especially a high shock resistivity is essential for the mentioned applications. Up to now no commercial solution for a micromechanical two-axes- inclinometer-sensor is available which fulfils these demands. A two axes inclinometer-sensor has been realized by S-bulk micromachining, using etch-compensation for convex corners and electrochemical etch stop for tight thickness control of the flexible Si-beams. The design procedure was assisted by 3D-FEM simulation of the mechanical and electrical (piezoresistive effect) behavior of the sensor thus resulting in an optimized layout of the sensor. The sensitivity can be easily adapted between 0.1 and 1 mV/(^{o} inclination) depending on the desired shock resistivity which is about 100g even for the most sensitive layout. To protect the sensorchip a low temperature bonding process has been developed. The sensors work properly in the range of $\pm 80^o$ inclination. The coarse concept of the sensor was developed using analytical approximations and fast 2D FEM-simulation,using Ansys.

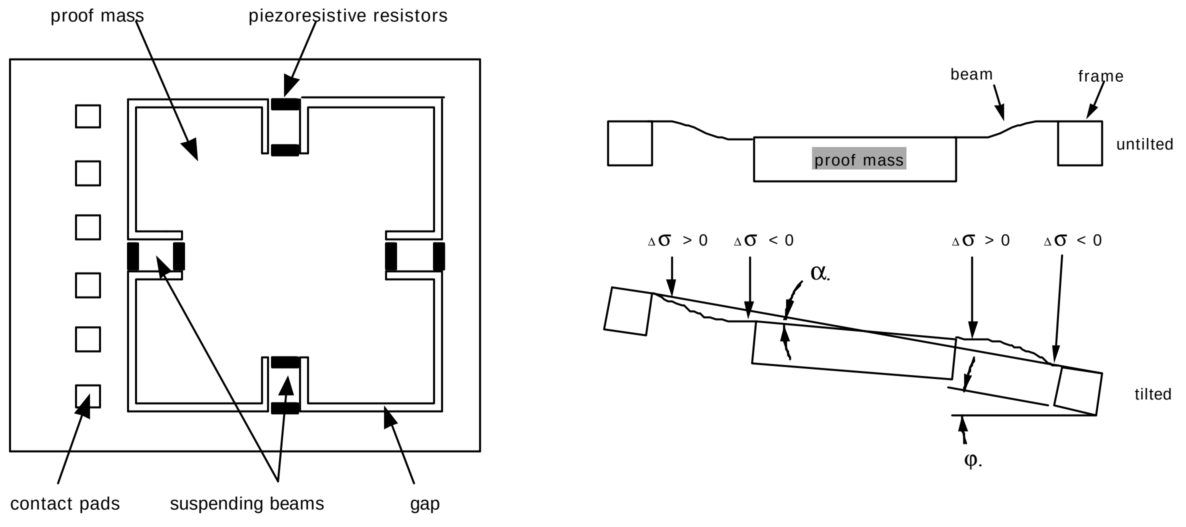


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Figure 5. a) Coarse concept of the inclinometer sensor. This beams hold the central seismic mass., the beams are defined in little gaps of the mass; b) Work Principle.

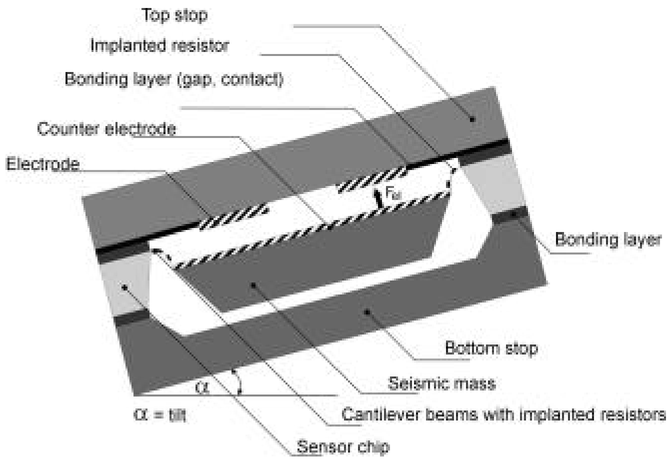

Figure 6: Encapsulating the sensor chip in between two cap layers one containing a four segment electrode structure, a close loop principle is realised.

5.1 Sensor Concept

The coarse concept of the sensor was developed using analytical approximations and fast 2D FEM-simulation (ANSYS). Regarding to concrete industrial specifications it was chosen the concept shown in Figure 5. A central proof mass is suspended by 4 thin Si-beams to the outer frame. The beams are located within little gaps of the proof mass. Compared to other approaches for accelerometer sensors (E.Graf,1993), this layout has the advantage of considerable large sensitivity. The sensitivity sensitivity reaches a maximum for a certain relation of beam length to sensor size. For a given sensor size of 5x5 mm^2 and the same geometry of the suspending beams the sensitivity is improved by a factor of about 2.4 (U.Mescheder,2003). As transducer principle we have chosen the piezoresitive effect which results in a relative signal change for a given inclination which is about 60% larger than for a capacitive readout assuming the same geometry. The tilt angle can be extracted from the output of two Wheatstone bridges. A tilt of the sensor around one axis results in a S-shaped distortion of the beams perpendicular to the tilt axes. The beams parallel to the tilt axis are torsional stressed. By placing the resistors perpendicular and symmetrically to the longitudinal direction of the beams an arbitrary tilt situation can be determined from the voltage drop at the two Wheatstone bridges.

5.2 Fabrication process of Tilt sensor

The sensor was realized by a 8 lithography-mask process using p-Si(100)-wafers and double side processing. A precise alignment of all structures to the crystal axes is required to ensure a symmetric placement of the beams and the implanted resistors within the gaps which are defined by KOH-etching from the back. This is achieved by anisotropic etching of the top side of the wafer at the beginning of the fabrication process to define alignment marks orientated precisely in [110]-direction. The thickness of the thin beams is controlled by an electrochemical etch stop. Therefore, 5um deep n-zones are defined by ion-implantation and diffusion. To prevent underetching of the convex corners,Fig.6, compensation structures are used. However, no complete compensation is possible because of the limited space available for the compensation structures.

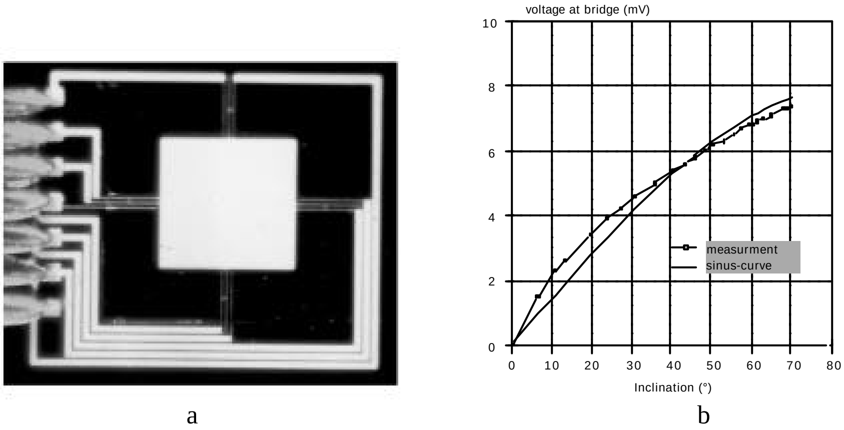

Figure 7. Bulk-micromachined tilt sensor, a: image of sensor with central seismic mass and very thin beams to the frame, b: sensor output.

In the final processing step the proof mass is released by RIE from the front side. The processed sensor wafer is capsuled between two Si-wafers. For this purpose the protecting wafers are spincoated with PMMA (thickness about 5um). Due to a special additive the PMMA can be structured by conventional photolithography as negative working resist. The bond of the cap wafers to the sensor-chip is performed at low temperatures with little load onto the wafers. In Figure 7(right) a measurement results of an unpacked sensor in the range between 0^o and 70 is shown. The output signal has a sinusoidal like shape(full line). Highest sensitivity is found for small inclination angles.

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