

Development and fabrication of a very High-g sensor for very high impact applications

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Abstract. In this paper we present the first time our development work of a family of silicon on insulator (SOI)- based piezoresistive MEMS very high G sensors for measurement of accelerations up to 60.000 g. Two sensors have been realized, one for 20.000g and one for 60.000g.

1. Introduction

Piezoresistivity is first discovered by Lord Kelvin in 1856, it is defined strictly to whose electrical resistivity changes with applied mechanical stress or strain. Many material exhibit piezoresistivity when strained, but the effect is most pronounced in semiconductors. Piezoresistive acceleration sensor is one of attempts by using the piezoresistive effect. The sensor in this work does have a silicon beam with 4 integrated piezoresistors. The sensor geometry of the sensor is optimized for high acceleration range up to 60.000g. Figure 1 shows a sketch of the top view of the sensor design.

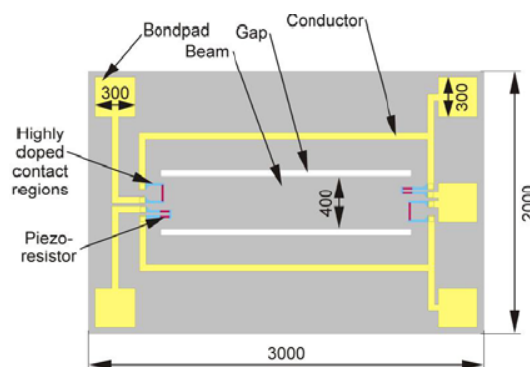


Figure 1: Sketch of top view of sensor design featuring one double-clamped beam carrying one transversal and one longitudinal piezoresistor on each end of the beam. Piezoresistors and conductors are connected to form an open full Wheatstone bridge

2. Simulation

A piezoresistive sensor with a Wheatstone bridge transforms mechanical strain into a change of output voltage when the bridge is voltage feeded. The output voltage changes according to equation (Eq. 1).

$$\Delta U = U_0 \cdot \varepsilon \cdot k \quad (\text{Eq. 1})$$

(with ΔU representing the change of output voltage and U_0 the supply voltage of the bridge). To increase the sensitivity the piezoresistive gauge factor k and the mechanical strain ε can be increased. As the change of the gauge factor in silicon depends on the doping concentration but high doping concentration is not desirable because of the increase of thermal coefficient of resistivity (TCR) According to beam theory it is very effective to change geometrical parameters in order to obtain higher mechanical strain.

$$\varepsilon = (\rho \cdot f \cdot g) / (2 \cdot E \cdot h) \cdot l^2 \quad (\text{Eq. 2})$$

(With density ρ and Young's modulus E being fixed material parameters for a silicon sensor and load f and acceleration due to gravity on Earth g describing the load case) Only the geometrical parameters of the beam thickness h and beam length l can be changed to increase the strain.

The design of the sensor was evaluated using Finite Element simulation. The simulation was performed using a bottom up approach in ANSYS: Figure 2 shows the model used for the simulation. Because of the symmetry a half model could be used. The element size in the beam was set to $20\mu\text{m}$. All degrees of freedom of the model was limited at the ground of the sensor and one at the symmetric areas. Figure 3 shows the strain on top of the beam with 60.000g applied on a $1000\mu\text{m}$ long beam. Strain strongly increases at the border of the beam. To find the maximum signal output an integral of the strain was calculated using the piezo resistor length as integration length. Figure 4 shows the simulation results of the strain depending on the beam length. The strain clearly increases with increasing beam length.

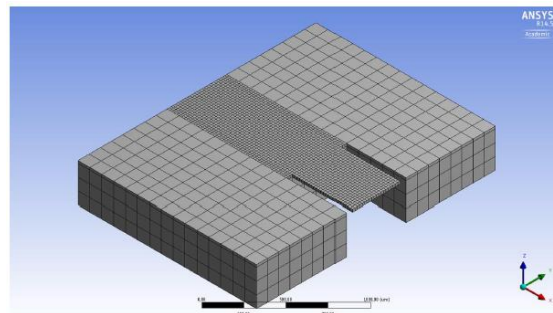


Figure 2 Meshed simulation model for FEA with fine meshing in the beam region

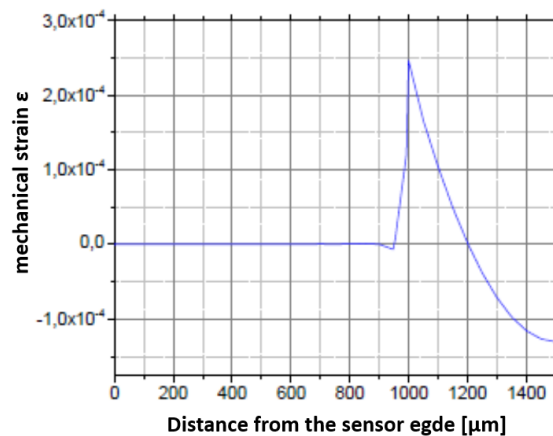


Figure 3 Mechanical Strain along the beam for a 1000 μm long beam accelerated with 60.000g.

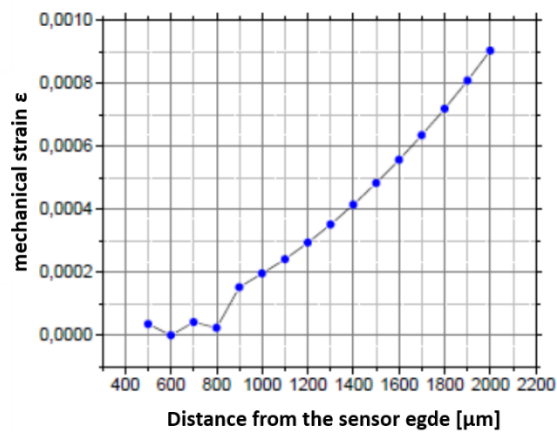


Figure 4 Mechanical strain at 60.000g in longitudinal direction for different beam length

Figure 5 summarizes the simulation results. It shows the calculated output voltage ($V_{\text{input}}=5\text{V}$) as a function of the beam length and the acceleration g . The output voltage rises with increasing beam length and with increasing acceleration. Limiting factor of the output voltage is the fracture stress of the silicon beam.

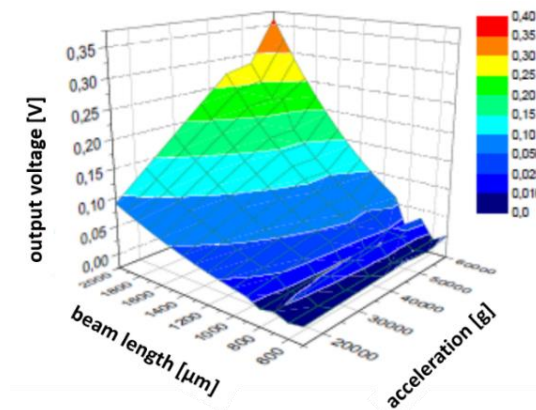


Figure 5 Sensor output voltage as a function of beam length and acceleration. The beam length was varied from 500 μm to 2000 μm and the acceleration from 15.000g to 60.000g

While the sensor sensitivity increases with increasing the beam length the resonance frequency decreases. The sensor design is always a compromise between the sensor sensitivity and its resonance frequency. In Figure 6 the simulation results of a modal analysis are shown. It can be clearly seen that the modal frequencies decrease with increasing beam length.

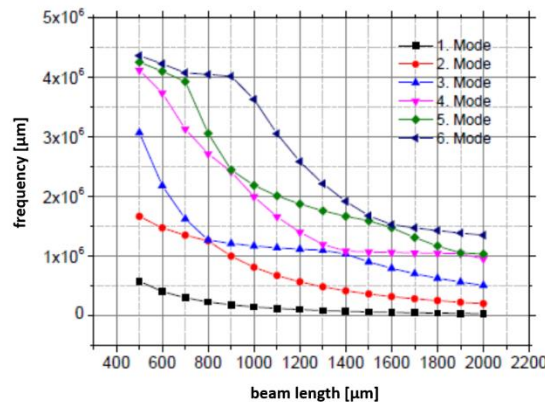
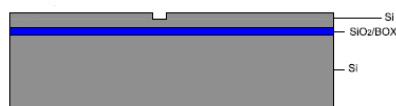


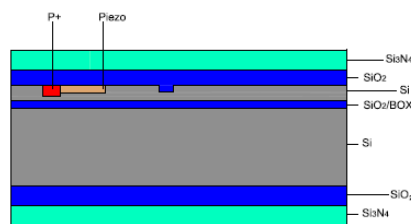
Figure 6 Modal analysis for the acceleration sensors for beam lengths from 500μm to 2000μm for the first six modes.

3. Device Fabrication

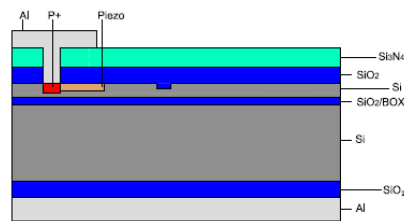
The sensors are produced from silicon on insulator wafers with a device layer thickness of 20μm. First implantation of the piezoresistors is performed with the help of a thin oxide layer. After the implantation the Wafer is passivated with a thermal Silicon oxide and a LPCVD Silicon nitride layer. These passivation layers are opened locally using lithography and dry etching before sputtering Aluminum. Afterwards this Aluminum is structured using lithography and chemical wet etching. Next the passivation layers on the backside are structured using dry and wet etching before a membrane will be etched from the backside using DRIE. The buried oxide layer is used a stopping layer. For processing the aluminum on the backside of the wafer is removed and the wafer is mounted on a carrier wafer. Using a further lithography step the passivation layers on top and the device layer is etched to generate slots which makes a double side clamped beam out of the sides clamped membrane. The carrier wafer is removed and anodic bonding is performed.



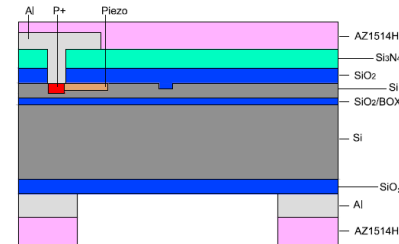
a) SOI Wafer with alignment marks



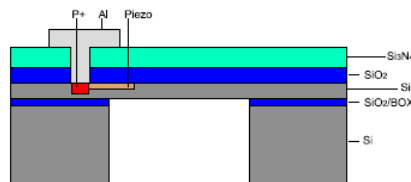
b) After implantation of piezoresistors silicon oxide and silicon nitride passivation layer was deposited



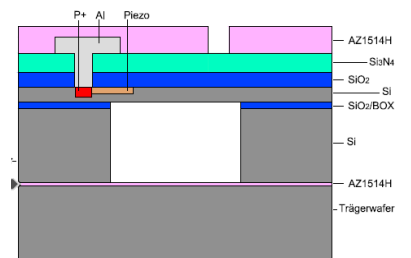
- c) Passivation layer was opened using dry and wet etching to contact the piezoresistors using aluminium.



- d) Frontside protection using photoresist and structuring aluminium on the backside using lithography.



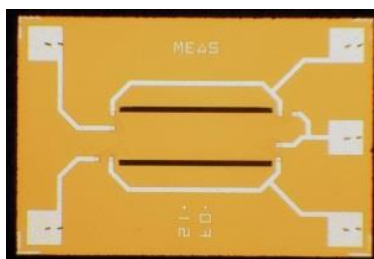
- e) Structuring the oxide on the backside and etching the membrane using DRIE



- f) Bonding temporarily to a carrierwafer and using lithography to generate the slots on the frontside generating the beam.

Figure 7 Main steps of device fabrication process.

The realized sensor element and packaged sensor are shown in Figure 8.



a)



b)

Figure 8 a) A realized MEMS high g sensor element (3x2x1mm³) b) Packaged high-g sensor.

4. Device Characterization

In order to generate the necessary accelerations, a Shock Wave Bar and a Polytech Vibrometer were used as an acceleration reference. The MEMS sensor element was attached to a stainless steel test fixture using standard die attach method. The die was wire bonded to the PCB where the output wires were soldered. A cover was added for protection. The test fixture was mounted to the end of the Shock Wave Bar. It also serves as the reference for the laser. Figure 9 shows the time domain by excitation at about 60.000 g. The sensor wave form tracks the laser signal very well.

A second approach for sensor characterization is to calculate the beam deflection caused by the acceleration of the sensor and use a micro actuator to deflect the beam and measure the resistance change. This allows linearly increase the deflection and observe the resistive change of the Wheatstone bridge.

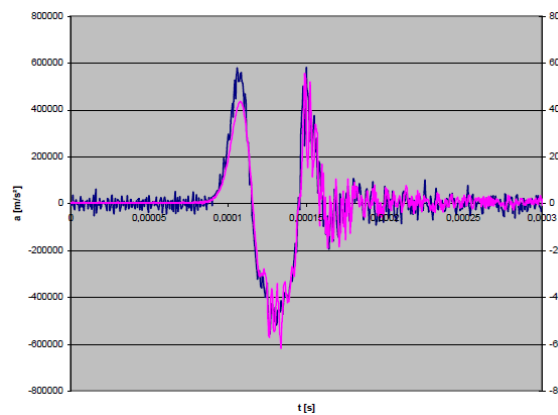


Figure 9: Test results of the 60.000 g sensor. Purple: MEMS sensor signal. Blue: reference sensor. A subsection

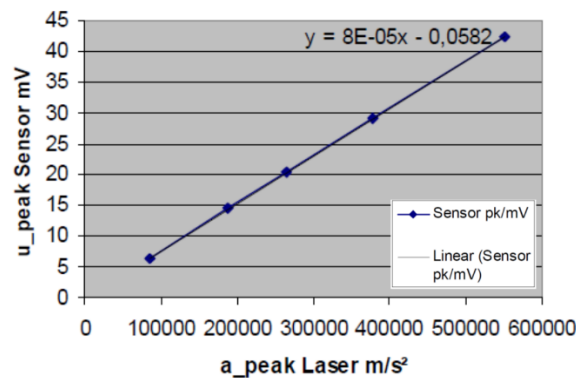


Figure 10: Calculated linearity of the sensor

Figure 11 shows the micro actuator mounted on a three axis table. With the three axis stage the actuator needle was positioned at the center of the beam of the sensor. The actuator is able to deflect the beam up to 30µm. Figure 12 shows the schematic of the measurement setup to deflect and measure the resistive change.

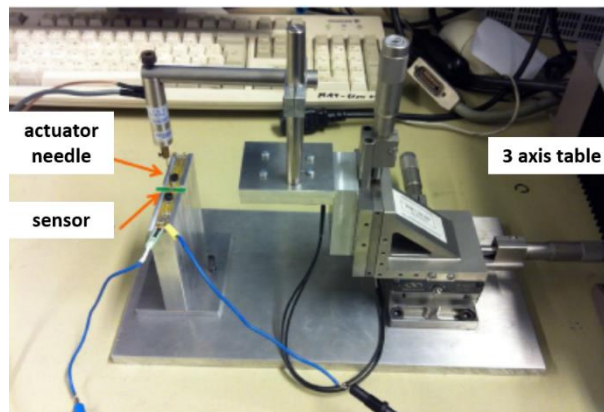


Figure 11 Photograph of the micro actuator used to displace the beam of the sensor. On the left side the sensor is located and the needle deflects the sensor beam. The position of the micro actuator needle can be positioned using the 3 axis table.

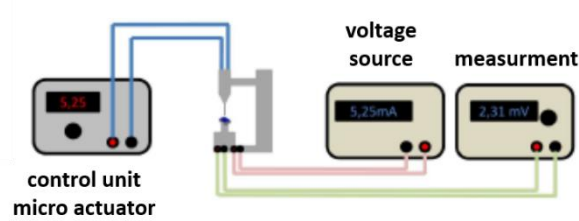


Figure 12 Schematic of the measurement setup to deflect and measure the resistive change of the sensor.

5. Conclusion

We present first time very high impact sensors for impact up to 60.000g. Before the sensor realization intense simulation work has been performed to find the best sensor design. The simulation results show a relationship between beam length and acceleration. The calculated output voltage increases with increasing acceleration and beam length.

The characterization of the realized sensor show a good match with the simulation results. The deviation of the measured output signal and the calculated output voltage is lower than 10mV for a beam length of 900 μ m and 60.000g. The sensors can be used in aerospace applications or in control and detection of impact levels.

Acknowledgement

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