Simulation of the Production of Functional Layers for Vibration Sensors for Tool State Monitoring and Finite Element Analysis of Mechanical Characteristics

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ABSTRACT

A novel MEMS vibration sensor for high acceleration amplitudes was developed in silicon technology for tool state monitoring. According to the application-specific requirements, the piezoresistive detection of vibration with polysilicon piezoresistors deposited on a thin silicon membrane is best suited. The technological parameters for the production of these strain-sensitive components were determined by ICECREM, a simulation program for processing steps in semiconductor production. The vibration characteristics, i.e. sensitivity, range, and resonance frequency, were predicted by analyzes with the Finite Element Method. Thus, design optimization for an optimum mechanical performance was executed. The sensor was manufactured by a CMOS compatible process. The measured sensitivity of over 20µV/Vg corresponds well with the simulation results, given the deviations of the sensor shape from the simulated values caused during the production process, and represents the highest known for this working range.

Keywords: vibration sensor, polysilicon, sensitivity, resonance frequency, design optimization

INTRODUCTION

Tool state monitoring has become a great concern in production industry as the requests for maximum quality of the work piece and optimization of processing time are simultaneously evolving. Tool wear, breakage, and collision between tool and work piece cause a lower work piece quality and lead to expensive machine downtimes. The surveillance of the tool vibration is a powerful means for an early detection of tool damages [1].

High signal quality is obtained if the vibration sensor can be mounted close to the insert, i.e. the cutting tool. In order to not disturb the process to be measured, the sensor has to be small. Of at least the same importance are reliability, robustness, and cost-efficency. These criteria can be met by using silicon technology for the sensor production. Silicon provides unique mechanical characteristics and robustness [2]; a mass production of sensor devices yields cost-efficient availability, especially if manufactured by a CMOS compatible process.

SET-UP OF THE VIBRATION SENSOR

Measurements of tool vibrations with commercially available sensors showed that accelerations of up to 4,000g ($1g=9.81m/s^2$) may occur when porous materials, such as cast iron, are cut. Signals in a frequency range at 5kHz were found to deliver information on tool wear and breakage. A close mounting of the sensor to the tool enhances signal quality but, on the other hand, makes an undesired heating of the sensor possible.

The high acceleration amplitudes and the frequency range make the piezoresistive detection the best choice. Polysilicon piezoresistors possess a lower temperature dependence compared to single-crystalline ones [3] and were therefore chosen for the detection. From the possible vibration sensitive structues - cantilever, bridge, and membrane - the membrane provides the highest resonance frequency per unit area [4]. Therefore, the developed vibration sensor consists of a thin silicon membrane with polysilicon piezoresistors. The vibration-induced strain within the membrane may be enhanced by adding a seismic mass to the membrane. Figure 1 shows a schematic cross section of the vibration sensor device in silicon technology.

The piezoresistors are connected to a Wheatstone bridge arrangement by the aluminum metallization. A passivation layer serves as protection against humidity and contamination. The membrane and the seismic mass are produced after the so far fully CMOS-compatible processing by anisotropic etching in potassium hydroxide (KOH) with an electrochemical etch-stop. The formation

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of a p-n junction is the necessary condition for this etch stop. Afterwards, the sensor will be housed and simultaneously damped by additional silicon chips on the upper and lower side, not shown in Figure 1.

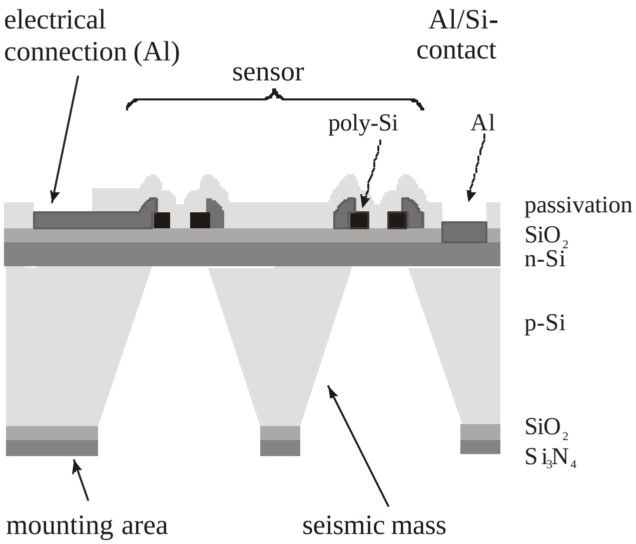

Figure 1 Schematic cross section of the vibration sensor for tool state monitoring

The shape of the seismic mass, the thickness of the silicon membrane, the placement, and the electrical properties of the piezoresistors determine the sensitivity of the sensor.

The overall sensitivity of the vibration sensor is given by

$$S = S_{mech} \cdot S_{el} = \left(\frac{\partial z}{\partial a_z} \cdot \frac{\partial \varepsilon}{\partial z} \right) \cdot \frac{\partial U_0}{\partial \varepsilon} \cdot \frac{1}{U_B} \tag{1}$$

where the mechanical sensitivity is composed by the membrane deflection z induced by an vertical acceleration a_z and the resulting strain ε in the membrane. The electrical sensitivity is defined by the piezoresistive coefficient or gage factor

$$K = \frac{\Delta R / R}{\varepsilon}, \tag{2}$$

with $\Delta R/R$ relative resistance change, which equals to the form written in eq. (1) in the case of a Wheatstone bridge with four piezoresistors, which is given here.

The sensor geometry determines also the resonance frequency. For a vibration sensor with a membrane without a seismic mass, the resonance frequency is given by

$$f_0 = \frac{35{,}99}{2\pi} \cdot \frac{d}{a^2} \cdot \sqrt{\frac{E}{12\rho \cdot (1-\nu^2)}} \tag{3}$$

with d thickness, a edge length of the membrane and E, ρ, and υ Young´s modulus, density, and Poisson ratio of the membrane, respectively.

Resonance frequency and sensitivity cannot be independently designed [5],

$$S = \frac{\beta \cdot 4\pi^2}{f_0^2}, \tag{4}$$

with β an efficency parameter depending on technological and geometrical properties. The following sections outline the design process for obtaining a vibration sensor with a maximum sensitivity at a given resonance frequency. A resonance frequency of 14kHz in the undamped state was imposed, as this allows enough resonance frequency loss caused by damping mechanisms.

SIMULATION OF THE PRODUCTION OF FUNCTIONAL LAYERS

The determination of manufacturing recipes for both the membrane thickness and the polysilicon doping and annealing was the aim of the examinations considered in this section. The manufacturing parameters were optimized by analyses with ICECREM, a simulation program for processing steps in semiconductor production [6].

The membrane thickness is mainly determined by the depth of the p-n junction. Thus, a n-type silicon membrane has to be formed in the p-type silicon substrate. A thickness of 10µm was considered mechanically stable enough for bearing the seismic mass. Previous work [7] indicates that the real membrane thickness exceeds the p-n junction depth by approximately 1µm. So, a depth of about 9µm was imposed. Besides the depth of the p-n junction the surface doping has to be adjusted for supporting the electrochemical etch stop. A ohmic contact has to be provided for the electrical connection of the n-type silicon membrane. A process sequence consisting of two separate ion implantations and subsequent annealings was found to meet both requirements best. The first implantation is followed by a drive-in step which provides the deep p-n junction. The second implantation produces the ohmic contact. The simulated concentration profile is plotted in Figure 2.

In the same way, the doping and annealing of the polysilicon piezoresistors was examined. The piezoresisitive properties of polysilicon depend strongly on the doping level

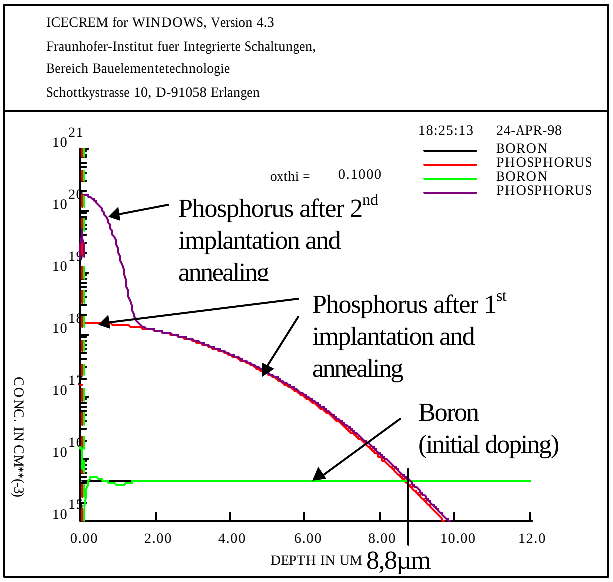

Figure 2 ICECREM simulation of the concentration profile after two phosphorus ion implantations (dose, energy) into p-type silicon and respective annealing steps (temperature, time):
(1) P, $5{\times}10^{14}$cm^{-2}, 200keV; 1100°C, 60h;
(2) P, $1{\times}10^{16}$cm^{-2}, 100keV; 1100°C, 1h

[8,9]. Both, gage factor, cfd. eq. (2), and the temperature coefficient (TC) of the gage factor increase with decreasing doping level. According to French [8], a p-type doping of 10^{19}cm^{-3} results in a optimum K/TC ratio. A boron doping of 10^{15}cm^{-2} with subsequent annealing at 900°C for 30min was chosen. Thus, a gage factor of approximately 30 can be expected [9]. The temeperature coefficient of resistance is expected to be $-1.5{\cdot}10^{-3}$K^{-1}.

Using these results as technological base for the Finite Element Analysis, the examination of the mechanical behavior was carried out.

FINITE ELEMENT ANALYSIS OF MECHANICAL CHARACTERISTICS

The mechanical sensitivity and the resonance frequency greatly depend on the shape of the sensor, i.e. its geometric properties. The optimization of the sensor geometry was carried out by simulating the vibration induced reaction of the sensor device. The resonance frequency of the simulated devices was kept constant to approximately 14kHz. The commercially available Finite Element Method program ANSYS [10] was used for this evaluation. The models for sensors with and without a seismic mass are shown in Figure 3. For symmetry reasons, the simulation of one quarter of the device is sufficient.
Figure 3 gives furthermore the strain in the sensor induced by a vibration with 50g at a frequency of 4.2kHz. The strain in a sensor with seismic mass exceeds the strain in a sensor with a pure membrane by one order of magnitude. This is accomplished by the concentration of the strain into a smaller area. Piezoresistors placed there will assume a higher strain. Moreover, the seismic mass can control the ratio between maximum compressive and tensile strain in the membrane surface. This is important when keeping in mind that polysilicon resistors can exploit longitudinal strain only. Using a membrane without a seismic mass, the strain in the membrane center is smaller by a factor of about -2.7 than the maximum strain reached at the membrane edge [11]. With a properly shaped seismic mass, tensile and compressive strain in the membrane surface at the rim and mass edges have the same amount what enhances the sensitivity of the Wheatstone bridge.

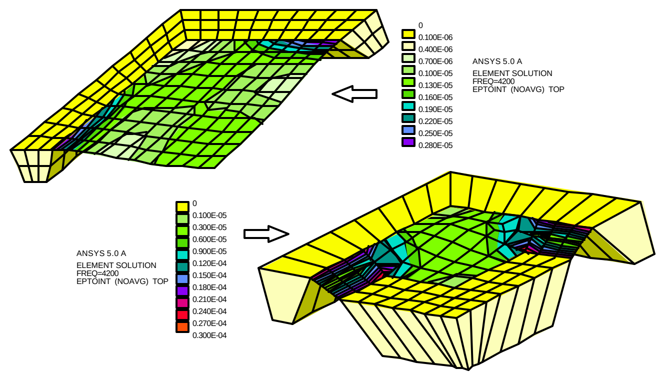

Figure 3 FEM simulation of strain (a.u.) in a silicon membrane with seismic mass (lower part) which is higher by one order of magnitude than in a membrane without seismic mass (upper part)

Various shapes of the seismic mass – square mass and symmetrical cross mass, as shown in Figure 3 - as well as different membrane edge lengths were examined. The effect of the underetching of convex corners by anisotropic etching was also included. Sensitivities of up to 30µV/Vg were attained. Table 1 summarizes the simulation results.

TEST RESULTS

Vibration sensors fabricated by means of CMOS compatible silicon technology with additional anisotropic etching were tested with a vibration excitation system. Figure 4 shows a measured output signal versus the excitation frequency. The vibration sensor measured exhibits a sensitivity of 21.3µV/Vg which corresponds well with the simulation result of 14.6µV/Vg given the deviations of the membrane and mass shapes from the simulated values caused during the production process. This shape deviation is also responsible for the occurance of the resonance frequency at a

Sensor type	Mass form	Membrane edge length (mm)	Range (g)	Simulated sensitivity, (µV/Vg)	Measured sensitivity, (µV/Vg)
1	No mass	3.162	>100000	0.85	n.a.
2	Square mass L=1477µm, W=1150µm	3.4	3300	19.5	25
3	Square mass L=1592µm, W=1300µm	3.6	3100	21.5	29.5
4	Symmetrical cross mass L=1537µm, W=767µm	3.6	5100	14.6	21.3

Table 1 Overview on different sensor types distinguished by the form of their seismic mass; given are geometrical parameters as well as the simulated vibration measurement range and sensitivity and measured values

lower point than in the simulation. More results are given in Table 1. Nevertheless, the measured sensitivity represents the highest known for this working range.

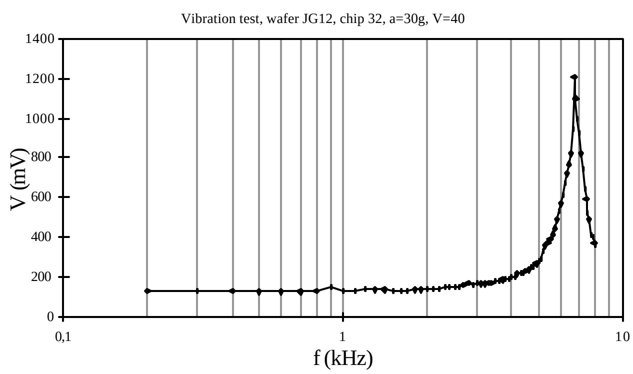

Figure 4 Vibration sensor output voltage versus excitation frequency; sensor of type 4 (cfd. Table 1); the excitation amplitude was 30g, the voltage gain 40, no additional damping was provided

CONCLUSION

A novel MEMS vibration sensor for tool state monitoring working in the high acceleration range is presented. The specifications for the manufacturing process in silicon technology and for a maximum piezocoefficient were obtained using ICECREM. In order to optimize the sensor sensitivity, its mechanical behavior was analyzed by means of FEM. Various shapes of the vibration sensor structure consisting of a membrane and a seismic mass were examined. Sensitivities of up to 29.5µV/Vg could be attained. The vibration sensor was fabricated in silicon technology with subsequent anisotropic etching. Test results correspond well with the simulation, given the deviations of the membrane and mass shapes from the simulated values caused during the production process . The measured sensitivity represents the highest known for this working range.

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