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Design and Fabrication of Piezoresistive Strain-Gauges for Harsh Environment Applications

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Abstract

Maximum operating temperature is usually one of the limiting factors for using of conventional sensors and other electronic devices. High-temperature sensors and electronics are required in some special applications e.g. measurement of deformations, stresses and pressures inside power generators. The design methodology of the some piezoresistive sensors utilizing FEM simulations is presented. Piezoresistive sensors based on thin-film metal sputtered layers, silicon-on-insulator (SOI) and nanocrystalline diamond layers (NCD) were successfully designed, fabricated and measured. The fabricated sensors are able to operate at temperatures up to 250 °C. Extensive study of sensor parameters e.g. deformation sensitivity, edge and contact resistances, temperature dependences gauge factor, bridge output voltage was performed. The measured values and investigated findings can be used for calibration of simulation software and in prospective design of more complex sensor structures.

Key words

piezoresistivity, strain-gauges, FEM, high-temperature application

1. Introduction

Piezoresistivity is one of the widely utilized physical phenomena in different kinds of sensor devices. Lord Kelvin referred that certain metalloid conductors subjected to mechanical strain exhibited a corresponding change in electrical resistance [1]. In general, semiconductors exhibit a much larger percentage change in electrical resistance per unit of strain than metals do. The piezoresistive effect in semiconductors was found to be much larger than that in metals by C. S. Smith in 1954 with germanium and silicon [2]. The basic function of the strain gauge is based on transforming the strain in certain direction as to change its electric resistance. It allows measuring plenty of non-electrical quantities such as deformation, bending, force, acceleration etc.

Various kinds of sensors of mechanical deformation have been developed. Those based on resistors implanted into a silicon substrate frequently have very good deformation sensitivity, linearity of characteristics, low hysteresis, etc. However, their resistors are usually electrically insulated from the substrate using P-N junctions. Due to temperature characteristics of the junctions their highest operational temperatures are limited only to about +130°C [3]. Higher operational temperatures (e.g. at least 200°C) are important for some sensor applications especially in mechanical engineering, power stations, etc. Besides the well known foil sensors also some thin film devices have been tested for such purposes [4].

The aim of this paper is to introduce specific design, fabrication and characterization techniques of high-temperature deformation sensors. Each used technology somehow improves the performance of sensors fabricated within the previous one.

The first piezoresistive sensors were based on the thin-film sputtered metallic layers. The aim was to find a material with reasonable deformation sensitivity. The materials used were e.g. Nichrome, Chromium Silicide and Tantalum Nitride. For application at elevated temperatures, a suitable contact system was developed and its optimization and stabilization of parameters at high temperatures was performed.

Next were the sensors based on SOI (Silicon-on-insulator). The SOI technology provides excellent compatibility with CMOS process and is suitable for operating temperatures up to 300 °C. Moreover, strain gauges based on crystalline silicon exhibits high deformation sensitivity.

Last were the sensors based on thin film nanocrystalline diamond layers. This technology is not as well established as the previous one, but unique mechanical and electrical properties of diamond promise applicability at very high temperatures. At present time, not only sensors of physical and electrical quantities are developed on diamond, but diamond layers are used in medicine and biomedical engineering as well.

2. FEM Mechanical and Piezoresistive Simulations

A. Numerical Solution using FEM

The Finite Element Method (FEM) was developed for numerical solving of mechanical stresses, deformations, temperature gradients etc., under elastic (linear) material behavior. In FEM, a distributed physical system to be analyzed is divided into a number (often large) of discrete elements. The complete system may be complex and irregularly shaped, but the individual elements are easy to analyze. The examined region is covered by a discretization net compiled from a finite number of generally 3D elements. The discrete element can have any shape from the simplest (triangles) to the very complex (tetrahedrons). Generally, the elements may be 1-D, 2-D (triangular or quadrilateral), or 3-D (tetrahedral, hexahedral, etc.) and may be linear or of higher order.

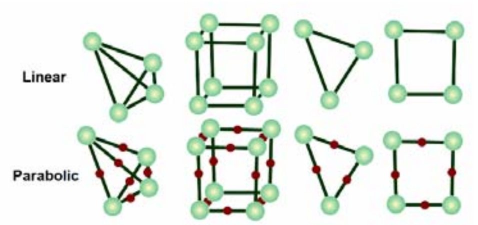

Fig. 1. General FEM elements

Advantages of FEM - a) usability for wide spectrum of shapes, b) easy generation of system matrix coefficients in the given net, c) useful properties of system matrix (e.g. conditionality), d) boundary conditions are fulfilled automatically
Practically, the only one disadvantage of this method is generation of the discretization mesh. Modern simulation software (e.g. CoventorWare) contains strong tools for mesh generation that make this action easier.

B. Mechanical and Piezoresistive Models

The piezoresistive analysis will be introduced on membrane pressure sensor. The sensitivity analysis was performed on two resistive elements, the meander and the straight resistor. The meander was moved along the centre line (y = 0 mm) while the straight resistor along line with position y = 550 µm The initial position is in the centre of the membrane and the structure is then moved with positive and negative offset.

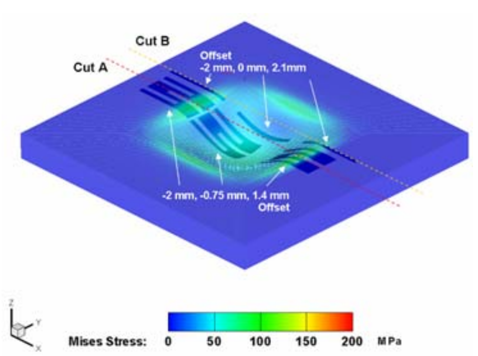

Fig. 2. Mechanical analysis - membrane deflection under applied pressure, and sensitivity analysis of meander and straight resistor

By the membrane bending, high-stress regions were growing up close to the membrane border and in the middle of the membrane (Fig. 2). The resistor placed on the border was subjected to tensile stress while resistor placed in the centre was subjected to compressive strain. This feature is very useful and finally, it increases the sensitivity of the sensor.

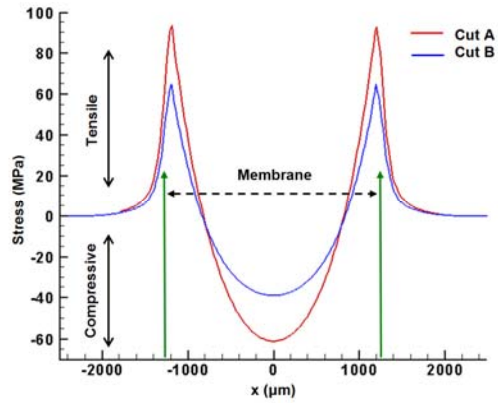

Fig. 3. Stress distribution along the centre line of the membrane (Cut A) and off the centre (Cut B)

The stress distribution is clearly visible in Fig. 3. There were two waveforms extracted from the membrane centre line (y = 0 mm, Cut A) and between the centre line and membrane border (y = 550 µm) as is depicted by dashed lines in Fig. 5.23.
The result of the sensitivity analysis (Fig. 4) shows that meander resistor R1 corresponds with the curve of mechanical stress very well, while straight resistor R2 does not exhibit such a big change in resistance as R1. The reason is, that R2 is little bit out of the area of highest stress.

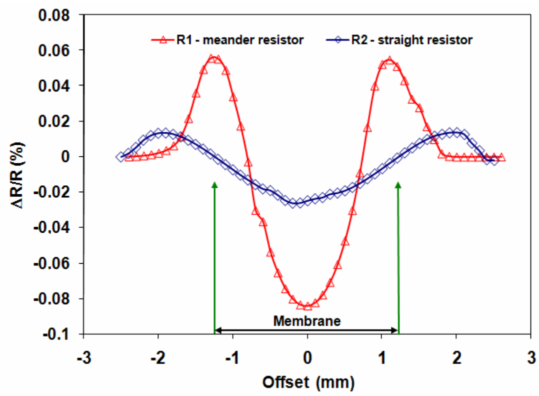

Fig. 4. Piezoresistive sensitivity analysis of the meander resistor (R1) and the straight resistor (R2) and their dependence on offset

C. FEM Modeling of piezoresistive SOI cantilever beam sensor

Designed topologies on the SOI substrate were mainly meander like structures with four resistors forming the Wheatstone bridge. The design started from the known substrate resistivity 0.02 Ω•cm, thickness of the device layer was 2 µm. Then, sheet resistivity was Rs = 100 Ω. The piezoresistive bridge should be compact and symmetric to achieve the same stress distribution for all resistors.

Three open bridges were designed with particular meanders of 450 µm, 900 µm and 1800 µm in size. Fig. 5. depicts mechanical simulation of the cantilever beam made of a SOI wafer. The beam was fixed at one side. The opposite side was loaded through force vector F = [0 0 2] N. The 3D models of meander structures (M450, M900 and M1800) are also depicted.

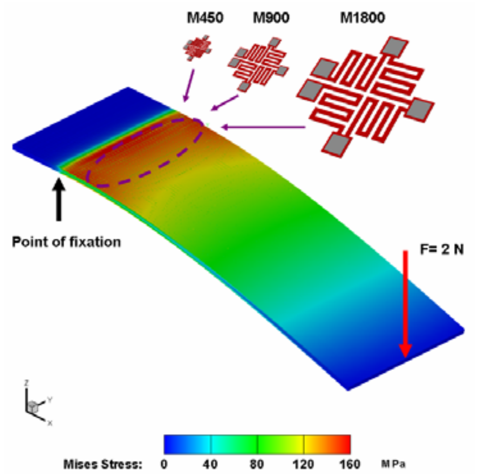

Fig. 5. Stress distribution in loaded beam, z-axis is magnified to see the bending

The aim of the simulation was mainly the calculation of the gauge factor and optimization of sensor position on the beam with respect to the point of fixation. The assumption for the simulation was that longitudinal and transversal piezoresistive coefficients are equal, it means, the resistance in longitudinal and transversal direction is the same.

Only one longitudinal and one transversal piezoresistor were taken into account during the simulation because of the bridge symmetry. It significantly reduced simulation time. Meanders were moved along x-axis of the beam in several steps. Offset means relative position of the centre of the meander with respect to the point of fixation. Stress distribution according to Fig. 5 was used for calculation of resistance. Meshed model of the structure M450 is shown in Fig. 6 and simulation results are depicted in Fig. 7.

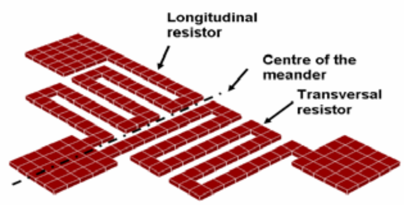

Fig. 6. Meshed 3D model of the structure M450, with longitudinal and transversal meander

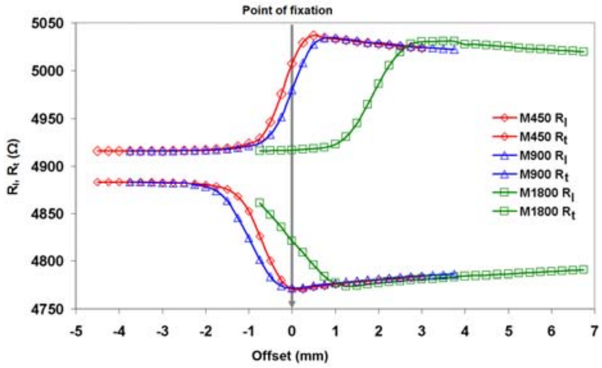

Fig. 7. Change in meander resistance in dependence on position with respect to point of fixation (Offset = 0 mm)

3. Realized Structures

Designed structures were successfully fabricated using three different technologies. The selection of the suitable fabrication technology was obeyed by requirement on higher operational temperatures of fabricated samples (among other). In practical applications, such as turbines for power generators, down-hole instruments, combustion engines, space exploration etc., operating temperatures of control and diagnostic systems are ever increasing and there is growing demand after electronics and sensors which can stand such harsh environment (e.g. temperatures over 150°C).

A. Strain Gauges with Thin-film Metal Layers

The active piezoresistive Nichome layer was created by magnetron sputtering on insulated silicon substrate (SiO_2/Si). The insulation layer was of 2 µm in thickness. Designed topologies included single resistors, half- and full-bridge structures, TLM structures (for contact resistance measurement). Example of structure with membrane pressure sensor in package is depicted on (Fig. 8a)

B. SOI Strain Gauges

Fabrication procedure of SOI samples production will be introduced in more details. SOI substrate was used for sample fabrication (Fig. 7). Standard photolithography and wet etching of contact and tensometric layers were utilized to prepare the samples. The wafers were coated with UV-sensitive photoresist and lithographically patterned by exposing the photoresist to UV light through the first level mask (RESISTORS), and then developed. The photoresist in exposed areas was removed, leaving behind a patterned photoresist mask for etching. Wet etching was used to etch the silicon down to the oxide layer. CP4 acid solution was used to etch silicon. After etching, the photoresist was chemically stripped. The AlCuSi metal layer was sputtered on the wafer, then patterned (through the second level mask METAL) and etched to make electrical interconnections (Fig. 8b).

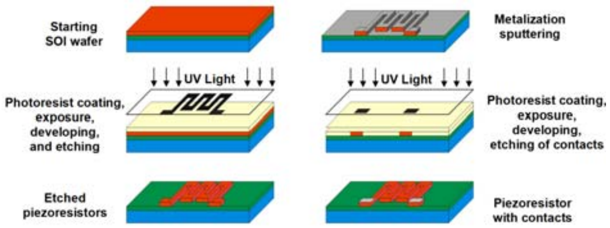

Fig. 7. Technological process of SOI sample production

C. *Strain Gauges with Nanocrystalline Diamond Layer*

Strain Gauges were created using directly patterned deposition (microwave plasma enhanced CVD process) of boron doped nanocrystalline diamond (NCD) layers on insulated silicon substrate (Fig. 8c).

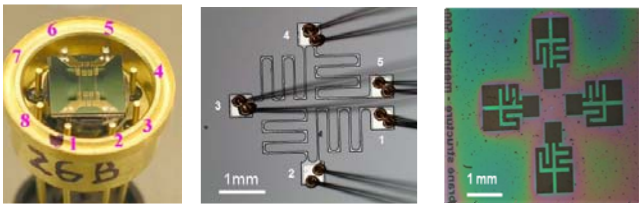
a) b) c)

Fig. 8. a) structure of membrane pressure sensor with NiCr piezoresistive layer; b) SOI strain gauges; c) strain gauges with NCD layers

4. Measurement Results

The extensive study of sensor parameters e.g. deformation sensitivity, edge and contact resistances, temperature dependences gauge factor, bridge output voltage was performed. A suitable contact system with stable parameters at elevated temperatures has been developed.
Kazi [5] reported in his extensive study regarding Nichrome strain gauges the GF in the range of 2 ÷ 2.5 (-), and TCR in the range of 100 ÷ 300 ppm/K (according to the layer thickness). We presented structures with NiCr layers exhibiting the highest deformation sensitivity of GF = 3.3 (-) and TCR = 30 ppm/K. It means higher sensitivity by 30 % at significantly lower temperature dependence.
The silicon strain gauges were etched in the surface single-crystalline layer, electrically insulated from the bulk substrate, enhancing the temperature range. In spite of relatively high doping level (resistivity 0.01 ÷ 0.02 Ω·cm), the sensitivity was still at a very good level (GF ~55).
NCD strain gauges exhibit higher gauge factor compared to strain gauges having sputtered metal layers. However, the gauge factor of NCD piezoresistors is still lower than that measured for SOI. The GF presented in this paper is 8.4 (-) at 25 °C for resistivity of ρ ~ 0.015 Ω.cm. The still relatively low GF value for NCD chips presented in this paper seems to be due to (not taken into account the resistivity) the lower grain size and lower film thickness [6],[7].

5. Conclusion

Modeling and simulation of mechanical stresses and deformations is virtually essential for any design of MEMS structures. CoventorWare software package was a very strong tool in the sensor design. Simulation results have opened the possibility for optimization of shape and position of the sensing elements on the deformation transducer to achieve the maximum sensitivity. Piezoresistive models presented in this paper were a little more optimistic (since the calculated sensitivity is higher than that measured) but still in good agreement with the measured values. Especially in the case of SOI strain gauges, the piezoresistive models were very accurate thanks to the fact that material properties (piezoresistive coefficients) for silicon are widely known. Conversely, the coefficients for diamond have not been published yet and piezoresistive simulation was made possible after their calculation from the measured values.
Several types of piezoresistive deformation sensors were successfully designed, fabricated and measured. FEM 3D modeling of mechanical, piezoresistive and temperature was performed. For the majority of fabricated sensors, the measured maximum operating temperature is 250 °C. However, it could be supposed that the temperature limit is even higher. The measured values and investigated findings can be used for calibration of simulation software and in prospective design of more complex sensor structures. The proposed newly developed sensor structures are very attractive for reasonable parameters and performance at higher operating temperatures. An innovative solution lies in using of nanocrystalline diamond layers and leads to very perspective sensors for measurement of mechanical quantities for application in harsh environment.

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