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Differential Strain Gage – A new Sensor Device for Microsystems

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Abstract:

The paper describes an operating principle for the electrical measurement of mechanical strain states. This principle gives up the idea of measuring the strain-induced resistance change of single wire conductors and passes on to determining the strain-induced deformation of the electrical field in area conductors. The basic operating principle, sensitivity considerations and the design of a functional prototype are described. Several experimental results in the application fields of transducer technology demonstrate the high capability of this method.

Key words: *Strain Gage, Sensor Design, Transducer Technology, Microsystems*

1. Introduction

For nearly 70 years, the bonded resistance strain gage has been one of the most powerful tools in the field of experimental stress analysis and transducer technology. Countless scientists and inventors have been engaged in the research and development of these devices. The particularly interesting early years are described in [1] and by now there is a growing number of specialist books [2], [3] and scientific publications [4], [5] covering quite different aspects of resistance strain gages.

The basic operational mechanism of these strain gages is the change of the electrical resistance in a conductor as a result of strain. The design of traditional resistance strain gages is also well known. Foil strain gages consist of a single resistance foil grid, structured in a high number of lead wires and end loops. For application in transducer technology, four strain gages are normally combined in a Wheatstone bridge. Disadvantages of this construction include the problems regarding the grid configuration, the difficulties in the process of temperature self-compensation and the limited scale of miniaturization.

In [6] is described, that also square semiconductor layers with a defined crystal orientation and symmetrically arranged contacts can be used to measure strain states. Furthermore is known, that special four-point surface resistors take also this interesting property [7].

On this basis, a new strain sensitive sensor, the differential strain gage (D-SG) has been developed and for the first time published in [8].

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2. Basic operating principle

Differential strain gages consist of a thin, square resistance layer with four symmetrically arranged electrical contacts. Two opposite contacts are connected with a voltage source. The other two contacts must be used to measure the output voltage.

The basic operating principle is shown in Fig. 1. In the initial state, the electric field caused by the voltage source is absolutely symmetrically distributed. That is, the measuring contacts are positioned on the same potential line and the output voltage in this state equals zero (Fig. 1a). Mechanical deformations in the resistance layer cause deformation of the electric field with the result that the measuring contacts are no longer on the same potential line and the output voltage is not equal to zero (Fig. 1b).

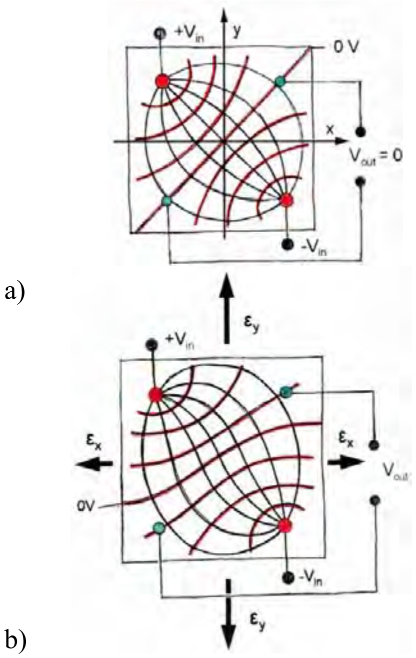


Fig. 1: Schematic drawing of the operating principle of differential strain gages, a) initial condition, b) deformed condition

Numerical simulations using the Finite Element System ANSYS 10.0 were to answer the following questions: How sensitive is this measuring principle? What influence do the changes in geometry and conductivity have? Model and results are shown in Fig. 2. The model for numerical simulation consists of 6400 square 8-node elements (et 121). As boundary conditions, voltages of $V_1 = +0.5V$ and $V_2 = -0.5V$ are impressed on points 1 and 2. The diagram represents the output voltage in the path between the measuring points 3 and 4 as function of strain and conductivity change.

The basic sensitivity Eq. (1) for the new differential strain gage must be written as

$$\frac{V_{out}}{V_{in}} = \kappa\left(\varepsilon_y - \varepsilon_x\right). \qquad (1)$$

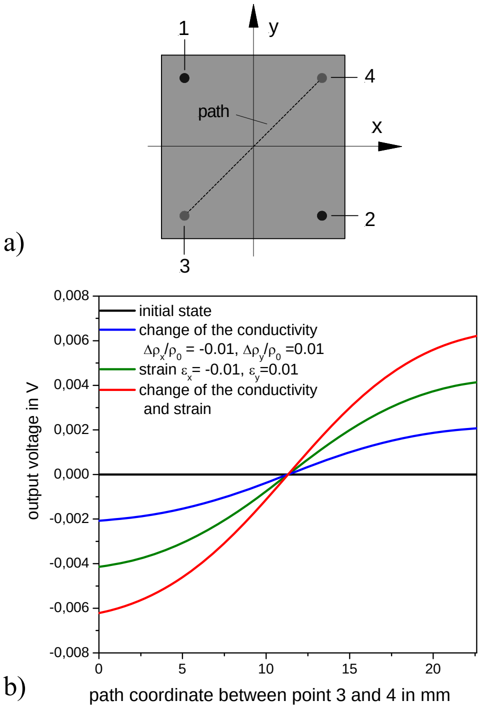
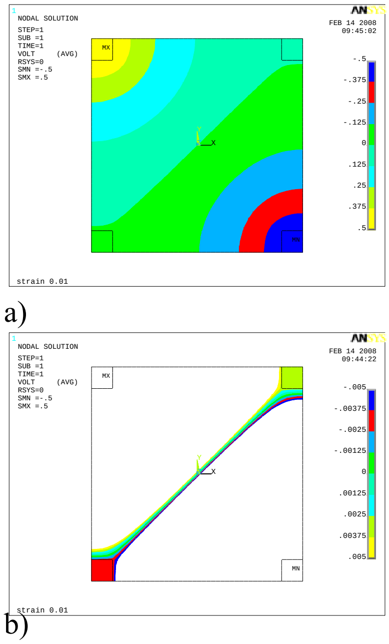


Fig. 2 a): Finite Element Model, $V_1=+0.5V$, $V_2=-0.5V$, $\rho=0.0005\Omega mm$,
b) Output voltage in the path in dependence of strain and conductivity change

A practical point of view is the position and the design of the contact areas. It is also favorable to contact the square resistance layer directly in the corners. The results of numerical simulation of this geometric layout are shown in the next two figures. Fig. 3 (above) presents the electric field in the strain state $\varepsilon_y = -\varepsilon_x = 0.01$. In the picture below, the scale is compressed by factor 100 so that the voltage difference between the measuring contacts becomes visible. The calculated output signal is $V_{out} / V_{in} = 0.0076V$ and the resulting geometric sensitivity is $\kappa = 0.38$.

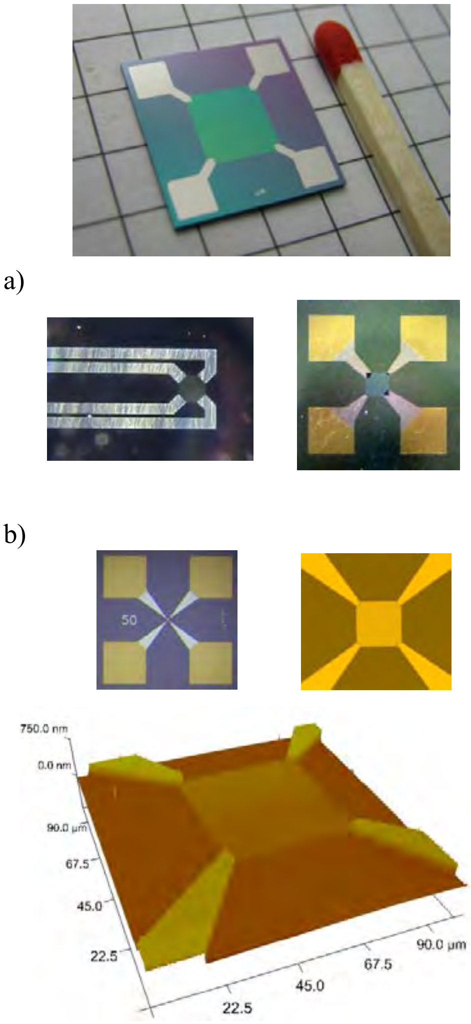


b)

Fig. 3: Calculated electric field, ε_y= -ε_x = 0.01, a) Full scale, b) Compressed scale by factor 100

3. Functional Prototypes

The functional prototypes of the strain gage sensor studied in this paper were prepared on standard (100) silicon wafers with a diameter of 3 inch and a thickness of 350 µm. The surface finishing of these commercially available substrates consisted in a front side polishing and a back side wet chemical etching including an oxidation treatment providing an oxide layer thickness of 1 µm. Details are described in [8]. In the Fig. 4 different design layouts in the size 6x6mm, 0.5x0.5mm and 0.05x0.05mm are shown. Installation was done using epoxy resin curing at room temperature.



a)

b)

c)

Fig. 4: Prototypes of D-SG a) 6x6mm b) 0.5x0.5mm, c) 0.05x0.05mm)

The connection of the D-SG to the data acquisition system is absolutely comparable to that of traditional resistance strain gages in a full bridge circuit. Normal strain gage amplifiers in full bridge configuration can be used (Fig. 5)

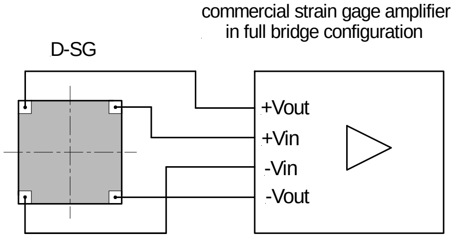


Fig. 5: Connection of the D-SG to a commercial strain gage amplifier

One of the major problems in strain gage technology is the influence of temperature. Two factors describe the influence of temperature on the output signal of traditional strain gages. First there is the fact that the resistance of most conductors changes with temperature

$$\frac{\Delta R}{R_0} = \alpha_R \Delta T\,. \qquad (2)$$

But the output signal of differential strain gages does not depend on the absolute value of the resistance layer. Provided that the resistance change is homogeneous in the complete area of the resistance layer, this temperature-dependent process does not have any influence on the output signal.

A second temperature effect occurs if the thermal expansion coefficient of the resistance layer α_{th}^{rc} is different from the thermal expansion coefficient of the structure α_{th}^{str} to which it is bonded. In the case of thermally isotropic behavior we get

$$\varepsilon_x = \varepsilon_y = \left(\alpha_{th}^{str} - \alpha_{th}^{rc}\right)\Delta T\,. \qquad (3)$$

Introduction in Eq. (1) shows that this temperature effect too does not cause any output signal.

$$\frac{V_{out}}{V_{in}} = \kappa\left(\alpha_{th}^{str} - \alpha_{th}^{rc} - \alpha_{th}^{str} + \alpha_{th}^{rc}\right)\Delta T = 0 \qquad (4)$$

The thermal output signals are presented in Fig. 6. This diagram also shows the apparent longitudinal strains. The signal of the D-SG is converted using a calibration factor just like in the application as strain sensor.

In spite of temperature adaptation to steel (temperature self-compensation) in the temperature range of $\Delta T = 32K$, the foil strain gage gives a thermal output of $\varepsilon_{app} \approx 27 \mu m/m$. There is also a notable hysteresis and the fact that the zero point is not reached after the temperature cycle.
In comparison, the curve of the differential strain gage is extremely flat. In the same temperature range, the thermal output signal is only $\varepsilon_{app} \approx 1-2 \mu m/m$. The hysteresis is much smaller and the zero point is very well reached after the complete temperature cycle.

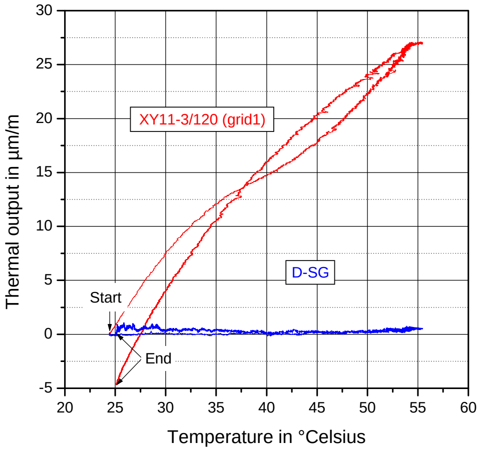


Fig. 6: Apparent strain during a temperature cycle

4. Application as platform scales

Application in the field of transducer technology is particularly interesting. Essential points in this context are the fact that both strain components act simultaneously and with different signals, Eq. (1), as well as the temperature stability. Fig. 7 shows an instrumented double beam for direct weighing of masses. The maximum capacity is 10 kg.

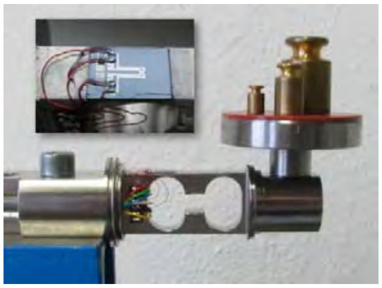
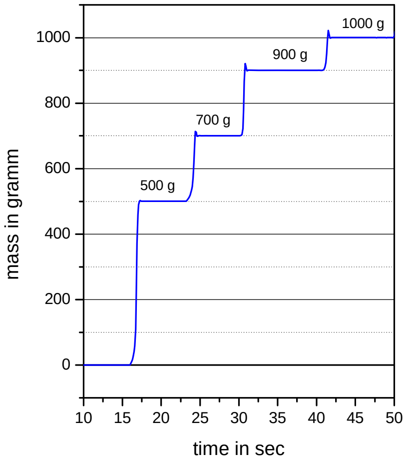
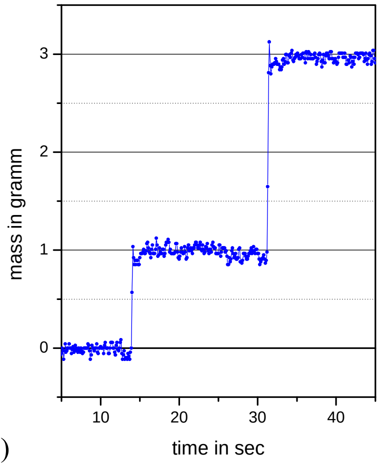


Fig. 7: Double bending beam instrumented with a D-SG 0.5x0.5mm as platform scale

Results are presented in the diagrams in Fig. 8. The scale is calibrated with a weight of 10 kg. The results show that all weights from 1g to 1000g are correctly indicated. The resolution is approximately 0.2g.



a)



b)

Fig. 8: Output signals at mass loads of a) 0 to 1000 grams and b) 0 to 3 grams

Fig. 9 shows the application of a strain gage with the extremely small resistant square dimensions of 50x50 µm.

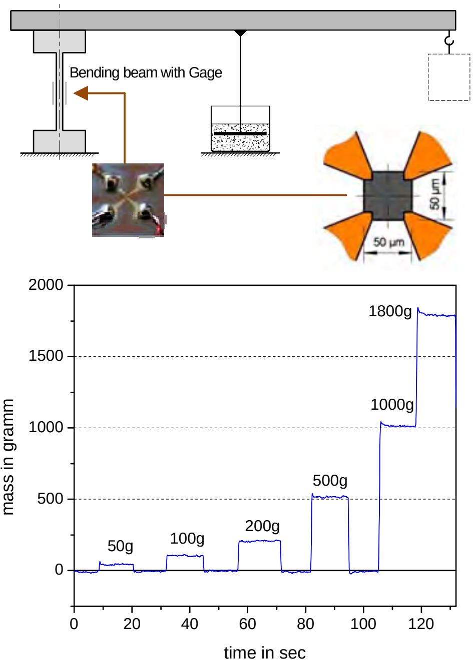


Fig. 9: Bending beam with D-SG 50x50 µm as scale

5. Conclusions

The presented differential strain gage is new and completely differs in function and geometry from the traditional resistance strain gage. The changed basic operating principle and the simple geometric design induce a lot of special properties and some science-based advantages. The following advantages refer to the production process, the measuring properties and temperature insensitivity:

- Simplification of the production process
- Application of new resistance materials
- Integration of the measuring effect over the complete area
- Insensitivity to defects in the resistant material
- Science-based temperature stability
- The process of foil treatment for temperature self-compensation is superseded
- Suitability of strain gages for different specimen materials

Experimental results show that differential strain gages are suited for use in transducer technology and, under certain conditions, also in experimental strain analysis. The simple design and the possibility to downsize all dimensions allow application in microelectro-mechanical systems.

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