J. Sens. Sens. Syst., 4, 91–95, 2015
www.j-sens-sens-syst.net/4/91/2015/
doi:10.5194/jsss-4-91-2015

JSSS Journal of Sensors and Sensor Systems Open Access

Thin film sensors for measuring small forces

F. Schmaljohann, D. Hagedorn, and F. Löffler

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Correspondence to: F. Schmaljohann (frank.schmaljohann@ptb.de)

Received: 31 October 2014 – Revised: 29 January 2015 – Accepted: 3 February 2015 – Published: 23 February 2015

Abstract. Especially in the case of measuring small forces, the use of conventional foil strain gauges is limited. The measurement uncertainty rises by force shunts and is due to the polymer foils used, as they are susceptible to moisture. Strain gauges in thin film technology present a potential solution to overcome these effects because of their direct and atomic contact with the measuring body, omitting an adhesive layer and the polymer foil.

For force measurements up to 1 N, a suitable deformation element was developed by finite element (FE) analysis. This element is designed for an approximate strain of 1000 $\mu m\,m^{-1}$ at the designated nominal load. The thin film system was applied by magnetron sputtering. The strain gauge structure is fabricated by distinct photolithographic steps.

The developed sensors were tested with different load increments. The functional capability of the single resistance strain gauges could be proven. Moreover, a developed sensor in a full bridge circuit showed a linear characteristic with low deviation and good stability.

1 Introduction

For many years, the use of resistance strain gauges (RSGs) for deformation measurements of parts has been state of the art. As a consequence thereof, the measurement of force is feasible with force transducers. The force is applied to a geometrically defined deformation element. Due to the deformation, the resistance of the applied RSG changes and, with the knowledge of the material parameters, the applied force, can be determined with high accuracy.

Most common are foil strain gauges, where the strain-sensitive pattern is applied to a flexible polymer foil or comparable backing material. These gauges are then fixed to the designated areas of deformation with a special glue.

Nevertheless, the measurement of small forces with foil gauges is limited, especially in the case of metrological intention. Sources of error that have an influence on the measurement uncertainty are located in force shunts with the RSG and with the susceptibility to moisture of the polymer foil. Additionally, the thickness of the backing material has to be mentioned, as this creates a distance between the actual deformation of the part and the strain-sensitive pattern. Furthermore, both the foils and the glue have a limited durability at high or very low temperatures.

Promising alternatives to foil gauges are thin film resistance strain gauges. The coating method and the subsequent structuring of the film allow an application directly onto the deformation element, without any kind of backing material except, at need, a thin insulation.

In 1992, Karaus and Paul (1992) presented a simple strain gauge based on thin film technology. Furthermore, the potential of this sensor technology for metrology was tested by a more sophisticated strain gauge applied to a 10 kN reference block. Thereby, a consistently higher sensitivity compared to conventional foil strain gauges was determined (Buß et al., 2008).

A technology has been developed at PTB to achieve thin film sensors applied onto metallic materials by sputtering, utilizing a thinner electrical insulation layer. In combination with a very flexible structuring technique, the fabrication is possible also for three-dimensional workpiece geometries (Hagedorn et al., 2007; Schmaljohann et al., 2012).

The high sensitivity and low creep behavior as stated in Buß et al. (2008) are due to the direct and atomic contact achieved by sputtering. In addition, the technology allows further miniaturization of the sensor and, hence, of the force transducer itself.

Published by Copernicus Publications on behalf of the AMA Association for Sensor Technology.

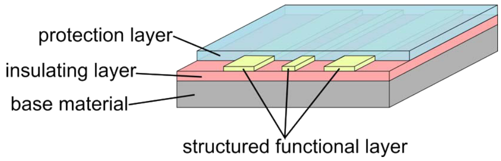

Figure 1. Film system used for the thin film sensors.

This paper presents the design of a compact deformation element for a nominal load of 1 N suited for the application of thin film strain gauges. In addition to the application of the sensors, different tests were carried out. Weights applied to the force transducer facilitate the functional support and its characteristic values. The developed prototype is connected in a full bridge circuit and demonstrates good stability and a linear behavior during strain measurement.

2 Thin film sensor technology

The thin film sensors introduced in this paper are initially based on an electrically insulating layer completely covering the body. By this layer, an electrical separation of the metallic and therefore electrically conducting deformation element from the following metallic sensor layer is achieved. If needed, a top layer can be applied to protect the sensor against environmental influences. The complete film system is depicted in Fig. 1.

To achieve the conductive paths and, thereby, the geometry of the sensor pattern, the second layer (i.e., the sensor layer) is structured by photolithography.

Consequently, there is no need for an adhesive layer and backing material, as is the case when using foil gauges. This makes the thin film sensor thinner by about 3 orders of magnitude.

2.1 Film system and application

All layers were deposited in magnetron sputter system "LS320S" by von Ardenne.

On the substrate, in this case the force transducer, an electrically insulating layer is deposited. This silicon oxide layer has a thickness of less than 5 µm.

Afterwards, an electrically conducting layer is applied, which serves as the sensor later on. Depending on the intended use, a suitable material can be chosen. In this work, a Cu–Ni alloy was chosen to ensure a low temperature dependency of the sensor. It is possible to match the film thickness to the desired sensor characteristics and, in this case, it is only a few 100 nm thick.

Subsequent to the structuring of the sensor layer, a protection layer can be sputtered on top. Again, this layer is made of an electrically insulating material such as aluminum oxide or silicon oxide.

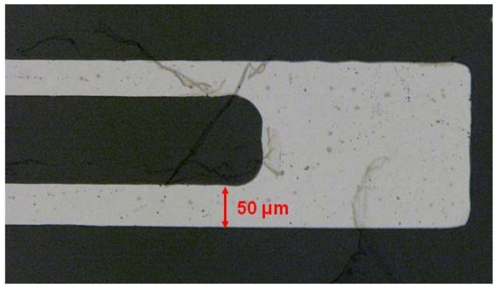

Figure 2. Detail of a structured sensor layer.

Thus, the film system has a thickness of less than 10 µm in total.

2.2 Structuring

The sensor layer is structured by a self-developed photolithographic process. Details of this process are covered in Schmaljohann et al. (2011).

The light-sensitive photoresist is sprayed uniformly onto the sensor layer. Afterwards, the paths of the sensor structure have to be exposed to light.

For this purpose, a UV light exposure system was developed and manufactured at PTB. The system is equipped with a blue-ray laser diode and specially adapted optics, so that the photoresist can be exposed with a precision in the micrometer range (Schmaljohann et al., 2013). In contrast to the commonly used exposure masks, the layout of the sensor can be changed easily. The demand for diverse requirements or dimensions of the sensors, which is especially the case in prototype construction, can be fulfilled by this very flexible technique.

After exposure, the photoresist is developed. The areas that were not exposed to light are removed and only the later pattern of the thin film sensor is protected by the resist for the next process step. The following wet-chemical etching process removes the uncovered part of the sensor layer. Finally, the remaining photoresist is stripped, leaving only the actual sensor pattern.

The thin film strain gauges presented have a structure size of about 50 µm. Smaller structure sizes can also be achieved by this process.

A detailed view of such a sensor structure is depicted in Fig. 2.

3 Force transducer layout

The goal in the engineering and design of the deformation element was to make it compact in size and suitable for force measurements up to 1 N. Furthermore, it should be possible to connect four RSGs in a full bridge circuit.

The computer-aided design of the force transducer was adjusted and optimized by the finite element (FE) analysis

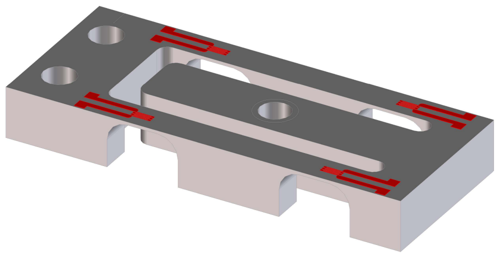

Figure 3. Deformation element as CAD model, utilized with RSGs in the areas of maximum strain.

method. After this step, the electrical properties of the RSG were calculated and the sensor design was fitted to the areas of maximum strain.

3.1 Development of the deformation element

By finite element analysis, a deformation element had to be found, which shows an elongation at the surface of 1 ‰ at a nominal load of 1 N. The material used for the design was EN AW-2024, a typical aluminum alloy for force transducers. Nevertheless, the prototypes were manufactured from the EN AW-2007 alloy because of its good machinability, while having a comparable material parameter.

The design of the deformation element has four areas of a defined and reduced cross section. The location for the application of force was selected such that under load, two deflection areas are elongated, while the other two are compressed in an equal manner. Therefore, the requirement for the installation of a full bridge is met.

Furthermore, the geometry of the deformation element allows the application of the full bridge on the planar upper side of the part. The limitation on only one side helps to simplify the surface coating and structuring process considerably.

The deflection areas had to be reduced to a width of 3 mm at a thickness of only 0.3 mm to achieve the desired strain of 1000 $\mu m\,m^{-1}$ at a load of 1 N. In contrast to foil strain gauges, the comparably small area is no problem for the application due to the miniaturization capabilities of the thin film RSGs.

The computer-aided design (CAD) model of the deformation element with the four areas for the strain gauges is depicted in Fig. 3.

Figure 4 shows the result of the finite element analysis under a nominal load of 1 N. The orange-colored areas mark the desired strain of about 1000 $\mu m\,m^{-1}$. At the same time, a higher stress is located in the boundary areas, illustrated by the red coloration. One potential reason for this occurrence are insufficient boundary conditions. However, as a stress step-up in this area is also quite possible, it will be considered for the sensor design.

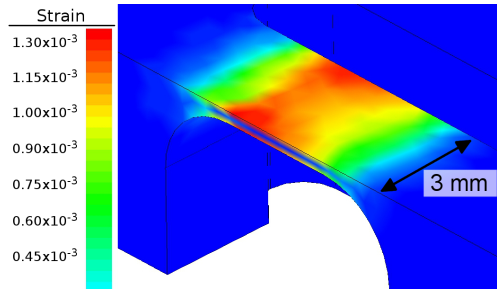

Figure 4. FE analysis of a single elastic deflection area of the deformation element.

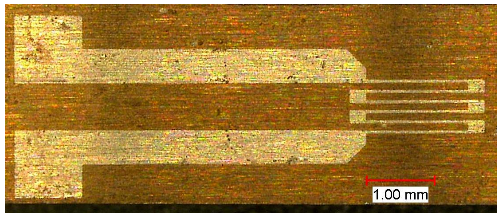

Figure 5. Overview of the structured thin film RSG.

3.2 Sensor layout

The layout of the sensor pattern was matched to the width of the deflection area and the result of the finite element analysis.

To get a sufficient but limited averaging of the strain measurement, a length of 1.5 mm for the strain pattern was chosen. With a structure width of 50 µm and a distance between the conducting paths of 100 µm, six parallel conducting paths are possible in total. Therefore, the total width of the strain pattern is only 0.8 mm. The influence on the force measurement by stress step-up in the boundary areas stated above is minimized. Two conducting paths with a width of 0.5 mm lead to the contact pads with a size of 1 mm^2 each.

Despite the small-sized sensor pattern, the layout stipulates a sensor resistance of up to 1000 Ω. This high resistance value, in comparison to other RSGs, should have a positive effect on the sensor's sensitivity, and it minimizes the impact of contact resistances and measuring lines. The high resistance value can be realized by a very thin sensor layer of about 100 nm, but, nevertheless, it can be changed easily to meet modified requirements by changing the layer thickness or by the line width of the structure itself.

Figure 5 shows a thin film RSG on a deformation element after the structuring process. A full view of the sputtered and structured deformation element is depicted in Fig. 6. For the following test procedures, thin wires were soldered to the contact pads of each RSG.

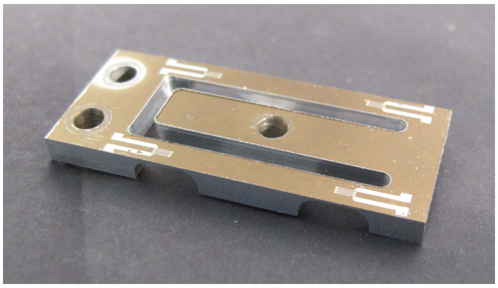

Figure 6. Deformation element with four sputtered RSGs in the deflection areas.

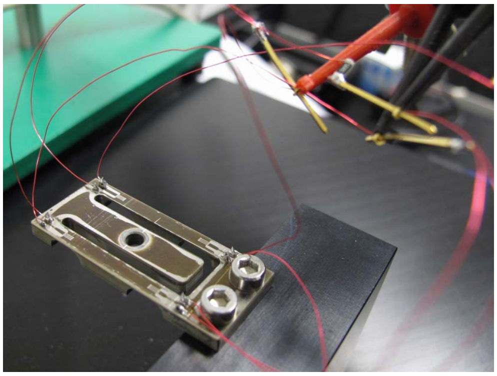

Figure 7. Measurement setup with a deformation element connected as a full bridge circuit.

4 Test procedure and measurement results

Initially, the base resistance of the RSG and the analysis of possible defects in the sensor structure, i.e., a good electrical insulation of the substrate, is of primary concern. Therefore, the electrical conductance of the sensor layer to the deformation element was checked with a lab multimeter.

Subsequently, for the functional tests, the sensors were connected to measurement amplifier “MX440A” by HBM GmbH. The force transducer is fastened at the two screw holes on one side. The measurement setup is depicted in Fig. 7.

In the first instance, only a quarter bridge, i.e., one single RSG and its shift of the resistance value, was measured. Hence, no compensation of the measurement bridge was needed. Instead, direct conclusions of the single sensors and their function were made.

The measurement procedure is based on the DIN EN ISO 376 international standard. The force was applied manually by calibrated single weights directly to the deformation element. During the measurements, the room temperature had a steady value of 22 °C.

After the connection of the sensor to the measurement amplifier, the measurements were not carried out until after an idle time of over 30 min. At the beginning of the tests, the resistance value and variation were measured at no load for 30 s. Afterwards, the load was increased in eight steps up to 100 g, which is about 1.0 N, pausing for 30 s between each step. The respective resistance measurement values were logged for 30 s at an interval of 1 Hz. At the end of the first series of measurements, a second one was started after an idle time of 3 min.

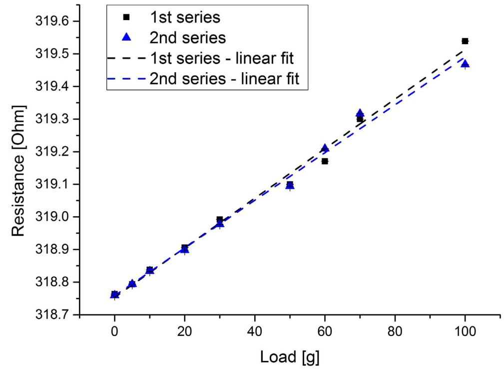

Figure 8. Diagram of the measured resistance of one single RSG and the applied load in grams.

For each step, the average value and standard deviation based on the 30 measurands were calculated. The results including the linear fits of a typical thin film strain gauge are shown in the diagram of Fig. 8.

The standard deviations of the values are not visible in the diagram as they are in the range of only 0.4 mΩ. During the tests, the sensors showed a very quick response and good damping behavior. Besides basic operation of the strain gauge, the test reveals the desired and almost linear characteristic. Nevertheless, differences in the two measurement series can be observed, possibly because of slight temperature changes that cannot be compensated for by this setup; this is one of the drawbacks in a quarter bridge setup, besides its limited resolution. Likewise, this might be the explanation for the slight deviation to linearity, and the occurrence of unwanted side forces is possible.

In addition to the measurement of one single RSG, four RSGs were connected in a full bridge configuration on another force transducer. The measured single resistances were in the range from 420 to 470 Ω. Therefore, the bridge was compensated for by additional resistors up to 470 Ω each. The rather small differences in the resistance values of about 10 % are due to slight variations in the width of the sensor pattern because of the wet etching step and, to a smaller degree, because of film thickness deviation.

The measurement procedure for this force transducer is the same as stated above. The results in the diagram of Fig. 9 reveal a very linear behavior over the full measurement range, much better compared to the quarter bridge setup. The calculated value of a strain of 1000 µm m^{-1} at the nominal load of about 1 N is reached. Moreover, the standard deviation of

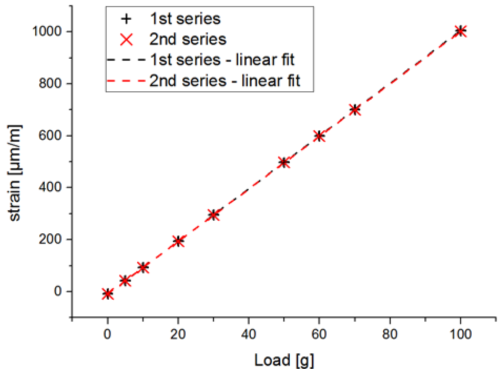

Figure 9. Diagram of the measured strain and the applied load in grams of a full bridge circuit

the single measurands is in the range of only 0.05 $\mu m\, m^{-1}$ (average of 0.03 $\mu m\, m^{-1}$).

A valid analysis of the measurement uncertainty was not conducted at the time of this writing, since this would imply better knowledge of the influences, for example, gravitational acceleration, and the accuracy of the weights. Nevertheless, besides the general functionality of the sensors in thin film technology, the results show the favored, linear dependence of the strain in the deflection areas and the change in resistance of the thin film sensor. Regarding the prototype status of the transducer assembly, the measured deviations of about 5×10^{-5} are very promising results.

5 Summary and outlook

The present paper shows the development of a force transducer for small forces up to 1 N in the metrological field. After optimization of the deformation element for the application of thin film sensors and small forces, the sensor layout was adapted to the deflection areas.

The coating and structuring technologies are applicable to the EN AW-2007 aluminum alloy and can be transferred to the EN AW-2024 typically used for force transducers.

The results show the general functionality and correct dimensioning of the deformation element and, in particular, the thin film strain gauges. The measurements based on international standards showed a very sensitive but stable behavior, with small deviations for a force transducer at this stage of development. In summary, the force transducer equipped with thin film sensors is very well eligible for measuring small forces up to 1 N. As a matter of course, the measurement uncertainty has to be determined to ensure its qualification.

The manufacturing procedures will be further improved to achieve full bridge compensation. In addition to the tests presented here, a comparison of the measured values with a deadweight force standard machine is planned, as well as long-term testing of the creep behavior. Likewise, the force transducer is to be tested for its adequacy for precision measurements in a special force standard machine for small forces (Schlegel et al., 2010). Because of the observed short response times and good damping behavior, dynamic testing of the sensor is needed.

Acknowledgements. The authors would like to thank Mr. Philip Heinisch for his support in the development of the light exposure system and his assistance in conducting the measurements.

Edited by: W. Daum
Reviewed by: three anonymous referees

References

Buß, A., Illemann, J., Kumme, R., Hagedorn, D., Meeß, R., and Löffler, F.: Entwicklung und Untersuchung von Kraftaufnehmern zur hochgenauen Messung statischer und dynamischer Kräfte, in: Sensoren und Messsysteme 2008, no. 2011 in VDI-Berichte, 2008.

Hagedorn, D., Meeß, R., and Löffler, F.: Fabrication of Sputtered Resistance Strain Gauges on Curved Surfaces, in: Proceedings of the 7th euspen International Conference, May 2007, Bremen, 2007.

Karaus, A. and Paul, H.: Load cells with small nominal load based on strain gauges using thin-film techniques, Measurement, 10, 133–139, doi:10.1016/0263-2241(92)90009-s, 1992.

Schlegel, C., Slanina, O., Haucke, G., and Kumme, R.: Construction of a Standard Force Machine for the Range of 100 µN–200 mN, in: IMEKO 2010 TC3, TC5 and TC22 Conferences, 2010.

Schmaljohann, F., Hagedorn, D., Buß, A., Kumme, R., and Löffler, F.: Entwicklung von Dünnschichtsensoren mit kleiner Strukturbreite auf dünnen isolierenden Schichten, in: MikroSystemTechnik Kongress 2011: Proceedings, 764–767, VDE-Verlag, 2011.

Schmaljohann, F., Hagedorn, D., Buß, A., Kumme, R., and Löffler, F.: Thin-film sensors with small structure size on flat and curved surfaces, Measurement Science and Technology, 23, 074019, doi:10.1088/0957-0233/23/7/074019, 2012.

Schmaljohann, F., Hagedorn, D., Meeß, R., and Löffler, F.: Blu-ray laser system for light exposure of photoresists on three dimensional surfaces, in: Proceedings of the 13th euspen International Conference – Berlin, 344–347, 2013.