DOI 10.5162/SMSI2025/B3.1

High-Sensitive Chromium Strain Gauges on Steel Surfaces

Rico Ottermann, Tobias Steppeler, Marc Christopher Wurz
Institute of Micro Production Technology, Leibniz University Hannover,
An der Universitaet 2, 30823 Garbsen, Germany
ottermann@impt.uni-hannover.de

Summary:
This article presents the photolithographic manufacturing and characterization of high-sensitive chromium-based strain gauges. They are produced polymer-free on stainless-steel tensile specimens and show high k-factors (strain sensitivity) of 11.0 ± 0.1. Their temperature coefficient (temperature sensitivity) of 591 ± 23 ppm/°C is comparably high which is why a full-bridge arrangement in cooperation with a temperature sensor next to it is used. This leads to a sensor system that can be used for harsh environment pressure measurements with a sensitivity of 1.71 µV/V/µm/m.

Keywords: Strain gauges, Chromium, Sputtering, Strain measurement, Polymer-free

Introduction

Strain sensors are crucial components in various industrial and research applications where precise measurement of deformation is essential. In industries such as aerospace and civil engineering, strain sensors provide real-time data on structural integrity, allowing for predictive maintenance, structural health monitoring and improved safety. Commercial strain gauges are polymer-foil based and attached with an adhesive to the measurement object [1]. Here, errors can occur due to different attachment conditions. Additionally, they have limitations when it comes to harsh environments like elevated temperature or chemical resistance [1],[2]. For this purpose, polymer-free thin-film sensors are used, for example for harsh environment pressure sensors [2]. Since mainly metallic components are of interest, the thin-film layers are deposited directly onto the surface based on the sputtering technology [3]. Because this technique allows not only the free choice of the sensor layer design but also its material, research is conducted concerning high-sensitivity materials. In comparison to standard materials like constantan or NiCr (k ≈ 2 [1]), extremely high k-factors of 174 can be reached with doped silicon but only in MEMS technology [4]. Sputtered materials such as Ni-DLC (Diamond-like-Carbon) show k-factors up to 15 with low temperature coefficient of resistance (TCR) [2]. CrN shows a strain sensitivity of 5-11 with TCR values of -5,500 ppm/°C to -186 ppm/°C [5],[6]. This article investigates sputtered chromium strain gauges on stainless-steel tensile specimens concerning their resistivity, k-factor, TCR as wells as full-bridge strain and temperature behavior.

Sensor Manufacturing

The strain gauges are produced on stainless-steel wafers (diameter: 100 mm, thickness: 0.8 mm). They are mirror polished with mean roughness values R_a = 20 ± 10 nm and R_z = 150 ± 80 nm. After a chemical cleaning step with acetone and isopropanol, sputter etching removes impurities and activates the surface for higher adhesion. First, a reactively RF sputtered Al_2O_3 insulation layer ensures electrical insulation of the following layer system.

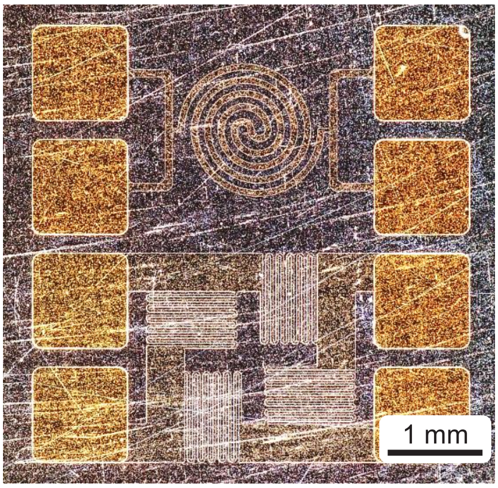

Fig. 1. Manufactured thin-film sensor system.

The total thickness of 2 µm is reached with two single steps of 1 µm with a chemical cleaning step in-between to enhance its functionality. Now, the photolithographic structuring takes place with the AZ5214E positive resist. The chromium sensor layer is sputtered with a power of 500 W (sputtering rate: 88 nm/min, sputtering pressure $3.8 \cdot 10^{-3}$ mbar). A final liftoff process results in meander-shaped single strain gauges and Wheatstone full-bridge circuits with a sensor layer thickness of 500 nm. A Pt temperature sensor (500 nm) with a Ti adhesion promoter (10 nm) and Au contact pads (500 nm) are fabricated with two further liftoff processes (Fig. 1). In the end, the wafer is cut into a simplified tensile specimen with a width of 40 mm. Solder contacting completes the sensor manufacturing.

Characterization

The insulation layer properties show a resistance of $9.7 \cdot 10^9 \pm 0.2 \cdot 10^8$ Ω that leads to a resistivity of $3 \cdot 10^{12} \pm 8 \cdot 10^{10}$ Ωcm. The breakdown field strength is 153 ± 25 kV/mm. The resistivity of Cr is $54.6 \cdot 10^{-6} \pm 1.5 \cdot 10^{-6}$ Ωcm that is approximately factor 4 of the bulk value which is in agreement with literature values [7]. The k-factor of four single strain gauges is characterized in a tensile test stand with forces between 400 and 2,400 N leading to a strain difference Δε of 312 µm/m. Based on the normalized resistance change $\Delta R/R_0$, eq. (1) is used.

$$k = (\Delta R/R_0)/\Delta\varepsilon \quad (1)$$

High k-factor values of 11.0 ± 0.1 were achieved. Fig. 2 shows the linear curve of several test cycles for Cr in comparison to NiCr with a k-factor of 2. An explanation of the increased Cr k-factor is assumed in partly semiconductor behavior through doping with oxygen or nitrogen which cannot be clarified in detail. The k-factor of Pt was reduced to 0.8 as a result of the symmetrical spiral sensor design.

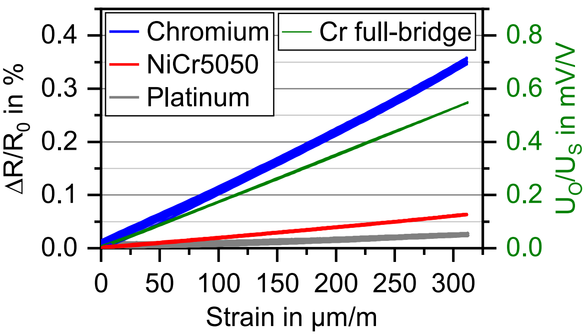

Fig. 2. Sensor signals for three different sensor materials and a Cr full-bridge.

Temperature investigations between 20 and 100 °C (ΔT = 80 °C) on a heating plate revealed TCR values of 591 ± 23 ppm/°C calculated with eq. (2). NiCr showed a value of 12 ± 5 ppm/°C.

$$TCR = (\Delta R/R_0)/\Delta T \quad (2)$$

Now, Cr strain gauge full-bridges were tested concerning their strain sensitivity, temperature behavior and drift behavior. Initially, the bridge offset is 6.9 ± 2.7 mV/V. The sensitivity is calculated to 1.71 ± 0.03 µV/V/µm/m based on eq. (3) [1], see Fig. 2. Here, the strain ε is given by the k-factor k, the poisson's ratio v, the bridge output voltage U_O and supply voltage U_S.

$$\varepsilon = 4/k \cdot 1/2 \cdot 1/(1+v) \cdot U_O/U_S \quad (3)$$

The temperature dependency leads to a high apparent strain of 4.4 µm/m/°C that can be reduced to a noise of only 11.7 µm/m in the temperature range from 20 °C up to 100 °C using the Pt thin-film temperature sensor. The drift at 20 °C is 0.36 µV/V/h that can be reduced with annealing.

Conclusion

This article presents sputtered chromium strain gauges on steel samples. With a k-factor of 11.0, the strain sensitivity is increased by a factor of 5 compared to conventional materials like NiCr. Due to the comparably high temperature coefficient of resistance of 591 ppm/°C (NiCr: 12 ppm/°C), Wheatstone full-bridge configurations were used leading to a strain sensitivity of 1.7 µV/V/µm/m. With an additional thin-film Pt temperature sensor, the remaining temperature induced apparent strain is 12 µm/m (20 °C up to 100 °C). These highly sensitive strain gauges can be used in harsh environments due to their polymer-free structure, and will be used for metal-based pressure sensors in the future.

References

[1] S. Keil, Dehnungsmessstreifen, *Springer Vieweg Wiesbaden*, Ed. 2, 1-485 (2017), doi: doi.org/10.1007/978-3-658-13612-3.

[2] M. Petersen, et al., Me-DLC films as material for highly sensitive temperature compensated strain gauges, *Diamond and Related Materials* 20, 814-818 (2011); doi: 10.1016/j.diamond.2011.03.036.

[3] R. Ottermann, M.C. Wurz, et al., Directly Deposited Thin-Film Strain Gauges for Force Measurement at Guide Carriages, *IEEE Sensors Journal* 24, 40471-40484 (2024); doi: 10.1109/JSEN.2024.3478821.

[4] S. Ling, et al., Novel Semiconductor Piezoresistive Thin-Film Strain Gauge With High Sensitivity, *IEEE Sensors Journal* 24, 13914-13924 (2024); doi: 10.1109/JSEN.2024.3373635.

[5] H.A. Mol, et al., Process for low temperature deposition of strain gauge materials based on Chromium nitride thin films, *IEEE Sensors*, 226-229 (2011); doi: 10.1109/ICSENS.2011.6127044.

[6] G.S. Chung, W.J. Lee, J.S. Song, Characteristics of Chromium Nitride Thin-Film Strain Gauges, *Sensors and Materials* 13, 13-23 (2001); sensors.myu-group.co.jp/article.php?ss=10426.

[7] P.A. Gould, The resistivity and structure of chromium thin films, *British Journal of Applied Physics* 16, 1481-1491 (1965); doi: 10.1088/0508-3443/16/10/309.