Veröffentlichung

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Autoren

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Titel

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Publisher o. Konferenz

ISMTII 2011, Daejeon, South Korea

Jahr

2011

Internet-Link (Doi-Nr.)

Analysis of a closed Wheatstone bridge consisting of doped piezo resistors

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KEYWORDS:Wheatstone bridge, pressure sensor, piezoresistive, balanced bridge.

In this paper, we present a method to calculate all four resistor values in order to balance a closed Wheatstone bridge. The Wheatstone bridge is an often used circuit for pressure or force measurements, where the applied bridge voltage is constant and the output voltage between the two midpoints is proportional to the measured load. For precise measurements, it is important to have an exactly balanced bridge. Balancing the bridge after the manufacturing process is only possible when the resistors' exact values are known. Unfortunately it is not possible to measure each single resistor because the other resistors are connected in parallel.

An analytic system is presented, which provides the possibility to calculate each resistor by measuring equivalent resistances between the corner points. Our method is unique because it provides a solution where all four resistance values are unknown. All other systems of equations found in literature need at least one known value. Another advantage is the simple realization of an automated measuring system.

In this article the method for analyzing a micro pressure sensor that has been developed in recent years at the IMT will be presented. Using this example, we will also describe the measurement principle and the entire micro fabrication process. Subsequently, we will discuss the challenge of the resistance measurement and the corresponding analysis of the Wheatstone bridge. Our system of equations for the exact calculation of each resistor will be derived from the original Wheatstone bridge equations. Finally we will make suggestions to manipulate the conducting paths of every single bridge on a wafer.

Manuscript received: March XX, 2011 / Accepted: January XX, 2011

NOMENCLATURE

R	= Electrical Resistance	[Ω]
U_I	= Input Voltage	[V]
U_0	= Output Voltage	[V]
T	= Temperature	[K]
ρ	= Electrical resistivity	[Ωm]
π	= Piezoresistive coefficient	[1/Pa]
σ	= Mechanical stress	[N/m²]

Indices:
1,2,3,4 number of resistor

1. Introduction

Due to the ever increasing demands of customers, ever more precise sensors must be developed. For this reason continuous investigation of new concepts is necessary to reduce their inaccuracy. Monetary aspects also have an influence on sensor development, leading to robust fabrication processes with high pass rates.

In micro fabrication, piezoresistivity is a frequently used principle to gauge a variety of physical measurands e.g. force, pressure and moments. Normally, four piezoresistors are placed on a tactile element, which convert a physical value into a change of resistivity. These resistors are wired directly onto a silicon chip. Micro fabricated chips are often housed in a robust closure, which makes it applicable in all industries and environments. In the last 40 years piezoresistive transmitters have become well-established all over the world.

Although the production and fabrication processes of these sensors is well established, improvements are still possible. One possibility for such an improvement is the novel method for balancing of a Wheatstone bridge as presented in this work. For the fabrication of novel pressure sensors, which are designed for precise measurements for fluid flow, four Wheatstone bridges were doped into silicon substrate [BEU10]. These resistors were placed on a membrane, which served as the tactile element as will be described later.

The doping process parameters are well known from previous investigations, but unfortunately some bridges continue to have varying resistances. This offset occurs due to the inequality of the four resistances. High offsets are problematic, because it reduces the maximum amplification and therefore decreases the sensitivity of the overall system.

Many electric circuits are industrially available which are able to compensate this effect. Specifically for sensor arrays, this solution may be an approach to enable the use of well established laser trimming technologies improved sensor signals on chip level.

2. Wheatstone bridge in microtechnology

Fig. 1 shows the basic components of a Wheatstone bridge including the numbering and the nomenclature used in this paper, which is the most common method.

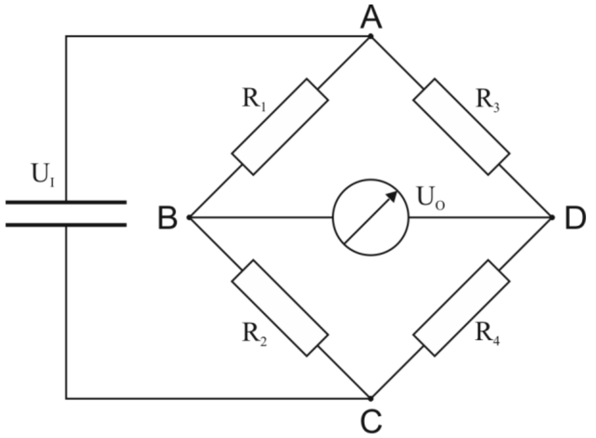

Fig. 1: Basic components of a full Wheatstone bridge

The input voltage U_I is applied at the corners A and C, while the output voltage U_O is measured at the points B and D. The resistors are numbered anti-clockwise starting at point A.

The Wheatstone bridge is used in order to achieve high changes in the output voltage with respect to relatively small changes in one or more resistor, while requiring very simple conducting path. In a so called full bridge, four resistors are varied, while in a half bridge only two are subject to such variations. In all circuits the total resistance can be calculated as follows:

$$R_{AC} = (R_1 + R_2) \parallel (R_4 + R_3) \qquad \text{Eq. 1}$$

Thereby R_1 is in series with R_2 and both are in parallel with R_4 which is in series with R_3. The output voltage can be calculated for all types of bridges by:

$$U_O = U_2 - U_3 = U_I \frac{R_2R_4 - R_3R_1}{(R_1+R_2)(R_3+R_4)} \qquad \text{Eq. 2}$$

One can see that the output voltage is 0 *V*, if $R_2R_4 = R_3R_1$. In this case the bridge is called “balanced”.

In a quarter-bridge circuit, only one resistor e.g. R_2 is variable, changing its value to $R_2 + \Delta R_2$. Hence, the output voltage U_O can be calculated as follows:

$$\frac{U_O}{U_I} = \frac{R_2 + \Delta R_2}{R_1+R_2 + \Delta R_2} - \frac{R_3}{R_3+R_4} \qquad \text{Eq. 3}$$

Analytical investigations show, that the maximum sensitivity $S = U_O/(U_I \cdot \Delta R)$ is obtained if all resistors are equal $(= R)$ when unloaded. Consequently, the equation can be simplified to:

$$\frac{U_O}{U_I} = \frac{1}{4}\frac{\Delta R_2}{R} \qquad \text{Eq. 4}$$

The same equation can be written for a full bridge, leading to the following relevant formula:

$$\frac{U_O}{U_I} = \frac{1}{4R}(-\Delta R_1 + \Delta R_2 - \Delta R_3 + \Delta R_4) \qquad \text{Eq. 5}$$

Summarized, a high sensitivity can be obtained, if the resistors’ values are equal when the mechanical stress is zero. It is obvious, that the sensitivity rises significantly if two resistances increase while the other two decrease, or vice versa. These equations are applied in microtechnology as they pertain to the piezoresistive effect.

In micro fabrication, piezoresistors are created by a p- or n-type diffusion of a doping agent into a semiconductor material like silicon. Therefore, the resistivity can be tuned to a desired value. If the size of the resistors are equal and the dopant concentration N is homogeneous, all resistors should have the same value of R.

The resistivity can be calculated as follows:

$$\frac{\Delta R}{\mathrm{R}} = \pi_L\sigma_L + \pi_T\sigma_T \qquad \text{Eq. 6}$$

where σ represents the mechanical stress in the longitudinal (index L) or transversal (index T) direction with respect to the current. π_L and π_T are the piezoresistive coefficients and depend on the doping process and the wafer material. These coefficients cannot be manipulated during the design process, but in order to maximize their effectiveness it is important to place the resistors at locations of maximum mechanical stress.

Typical values for π are listed in Table 1. These values depend on the diffusion process parameters (mainly temperature and diffusion time). The list is therefore only usedfor better understanding

Material	π_L [10^{-11} *1/Pa*]	π_T [10^{-11} *1/Pa*]
Si (p-doped)	+21.52	-19.83
Si (n-doped)	-9.36	-5.28

Table 1: Material and piezoresistive coefficients

The sign of p-doped silicon changes, depending on the direction of the current in relation to the mechanical stress. In practice, a resistor is either longitudinal, or transversal, because the mechanical stress in high in one direction, and close to zero in the perpendicular direction. The sign of ΔR also changes if the sign of σ changes. Hence, the position on the tactile element and/or the direction of the current, influences the sign of the resistance change ΔR.

Another advantage of the full-bridge is that it features temperature compensation. The piezoresistive coefficients are a function of the temperature. Resistance change due to temperature changes, which has a negative influence on the accuracy and linearity. By using a full-bridge all resistance changes are canceled out.

The previously mentioned facts show that there are many possible layouts for a high sensitivity full bridge. This flexibility of the Wheatstone bridge makes it attractive for measurements within micro electromechanical systems (MEMS). Eq. 6 indicates that along with the piezoresistive coefficients, the mechanical stress has a direct influence on the sensitivity. It is therefore important to place the piezoresistors in well defined locations on the tactile element.

A FEM simulation of the micro system was used to obtain very precise information about the mechanical stress distribution on the membrane, which is shown the next subsection.

3. Sensor Design and Simulation

The most crucial element of these doped silicon sensors is the positioning of the piezoresistors on the tactile element. The geometry depends on the physical measurand. For force measurements, a beam or stylus is needed. Acceleration is measured using a seismic mass, while pressure measurements require a membrane to convert the measurand into a mechanical stress. Fig. 2 shows some typical geometries. As one can see, the piezoresistors are always located at similar locations, specifically, wherever mechanical stress appears.

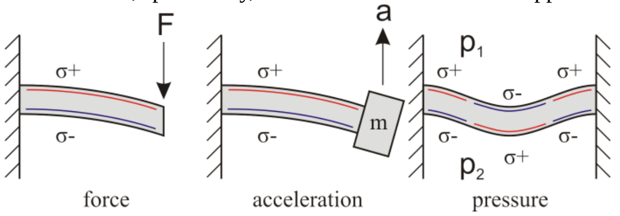

Fig. 2: Different sensor types using piezoresistive elements

As described before, determination locations of maximal mechanical stress is essential. For example, in the case of a pressure sensor the most significant fabrication and simulation processes are pointed out briefly in the following subsection.

The design of the membrane itself has a large impact on the maximum load and measurement properties e.g. linearity and resolution. Therefore, much effort is needed to develop a design, which has the desired properties and which is producible. In micro fabrication this is limited by the available technologies and by the type of wafer used [TIB08].

In every case, a FEM simulation was conducted to calculate the mechanical stress within the material. It was determined that the applied load must be much lower than the tensile strength in order to obtain a linear response. Nevertheless this load must be large enough in this measuring range in order to allow high sensitivity. Empirical data was used to define these limits.

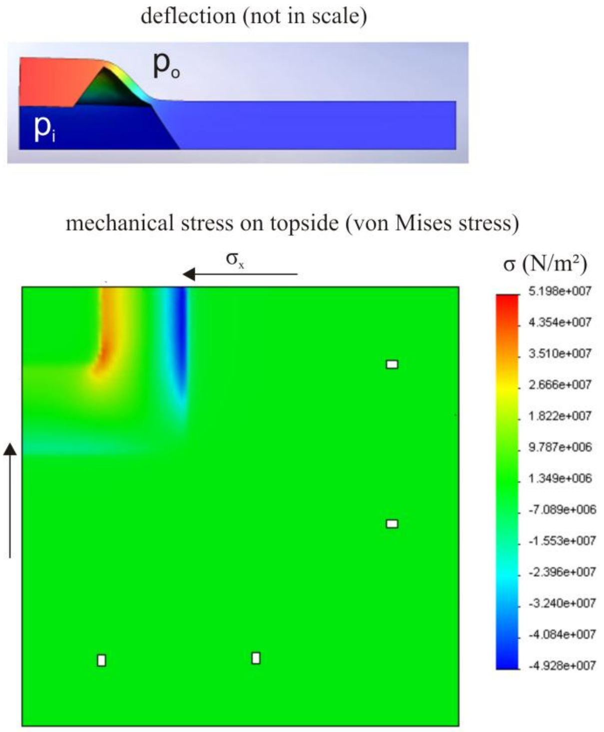

Fig. 3: FEM results of a silicon membrane ($p_0 < p_1$)

Fig. 3 shows the result of the FEM analysis of a pressure sensor with a diaphragm. The section view is indicated. Because of symmetry effects, only one quarter is simulated, in order to reduce the calculation time significantly.

One can easily see that the areas of maximum mechanical stresses are small. The stress is therefore not distributed over the entire membrane; rather it is concentrated in discrete locations. The resistors must be placed in these locations of maximum stress. Any variations will lead to a lower sensitivity. Fig. 3 shows the results for a membrane with a thickness of 45 µm. In a design iteration, the geometry would be adapted until the stress distribution fit the requirements.

When the design is finalized, the photolithographic masks are written and the micro fabrication begins. Typical process steps are shown in Fig. 4.

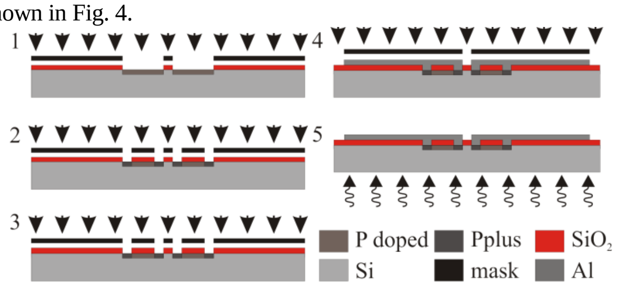

Fig. 4: Significant process steps to create a piezoresistive sensor

Initially a diffusion step is carried out (1). A thermal SiO_2 layer is then applied and structured, so that only the regions which are doped are left uncovered. A boron emulsion is applied onto the wafer using a spin coating technique. Diffusion is then performed in an oven at 900 °*C*. The oxide is then removed. The same process is used to prepare the second diffusion, but this time only the contact areas are doped (2). The process temperature has to bet set higher in order to get a highly doped regions. In order to avoid an electrical contact between the aluminum conducting path and the undoped silicon, a PECVD oxide is deposited over the silicon. This layer is then removed from the contact region (3). A metal layer is then sputtered and structured to create the desired circuits (4). It is essential to perform a tempering process at ca. 400 °*C* to get a homogeneous contact zone between aluminum and silicon. For other metals the parameters vary.

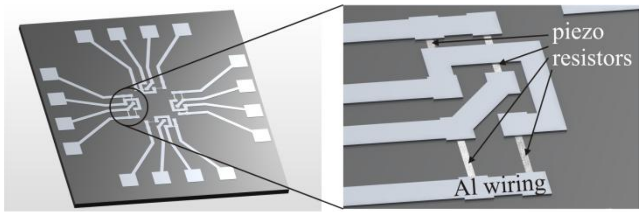

Fig. 5: Simulation of the sensor, with a detailed view on one full bridge. The piezoresistors have been marked

Fig. 5 shows that all piezoresistors are connected simultaneously by only one metal layer, which is the conducting path. Each resistor in the Wheatstone bridge is thereby connected to two others in step 4. The resistances change during the tempering process. Therefore, each single resistor in the Wheatstone bridge is the sum of three resistances, caused by the contact resistance between metal and doped silicon and vice versa. Fig. 6 illustrates this effect and leads to Eq. 7.

$$R = R_{Al-Si} + R_{piezo} + R_{Si-Al} \qquad \text{Eq. 7}$$

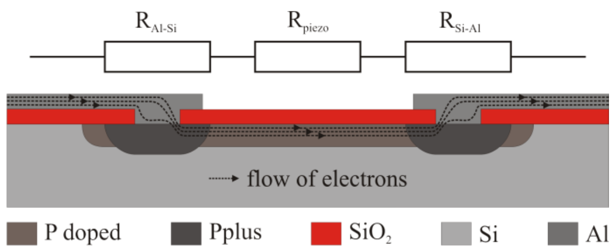

Fig. 6: Physical explanation of the contact resistance

During layout of the photolithographic mask all resistors have been designed with equal dimensions. In this way, all resistors should have the same value R_{piezo}. Due to manufacturing uncertainties these values vary in practice. The contact resistances R_{Al-Si} also have a tendency to fluctuate. The metal conducting path resistance also has an affect in unbalancing the bridge, which has been neglected in the scheme. The variation of R leads to reduced accuracy.

Summarized, the electric properties of the bridge depend on many variables, which are not completely controllable. Therefore, it is very problematic to produce exact balanced bridges. Typical measurement values are shown in Table 2 which demonstrate this effect.

Resistor	$R_{A\to B}$	$R_{B\to C}$	$R_{C\to D}$	$R_{D\to A}$	$R_{A\to C}$	$R_{B\to D}$
Resistance [Ω]	428	430	429	435	570	571

Table 2: Typical resistance values at a closed bridge

The impact of this problem on the maximum accuracy is non-trivial. In the example given in Table 1, the offset voltage $U_{O,Offset}$ in the unloaded state equals 3,5 *mV/V*. The sensors' sensitivity S, defined as the change in the output voltage U_O due to the pressure change p_{max} per Volt input voltage, is around 40 *mV/(V·bar)*.

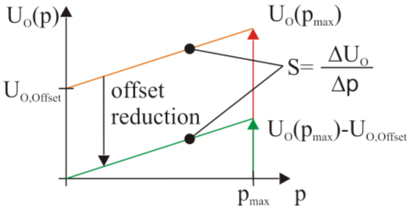

Fig. 7: Offset and measurements in the range of 1 bar

Because many DAQ Systems only operate up to a maximum of 10 *V*, the amplification factor is limited to 45 if the sensor is operated at 5 V. If the offset is close to zero, the amplification could be set to 50 or more with the same sensor properties. By using the presented method, the overall gain factor was able to be increased by the factor of $(U_{O,Offset}+S)/S$. For the given example, this value equals 1.0875, which is close to 10%. Fig. 7 shows this principle.

Often, more than one bridge is placed on the sensor, which leads to a decreasing in sensor quality. For sensor arrays, which are becoming more and more popular, the yield is reduced.

4. Analytical system of equations

Up to now, no method has been found to calculate the value of every single resistor in order to allow the trimming of their resistances. Methods for resistor trimming are known, but in the case of the full-bridge their application is extremely problematic. In [SEN01] this is pointed out very clearly.

In order to achieve a well calibrated Wheatstone bridge and consequently a precise measurement signal, it is necessary to know each resistance exactly. As a consequence of the microtechnological resistor fabrication process, the resistances are inaccessible; hence it is impossible to measure them. In order to allow continued access to precise results, a mathematical approach was chosen in order to identify each resistance.

The definition of the auxiliary variables S_1, S_2, S_3, S_4, S_5 and S_6 (see Fig. 8) are necessary because they are the only measurable values after the fabrication process. These variables are the equivalent resistances which describe the relationship between the four resistances R_1 - R_4. Thereby, S_1 is equivalent to R_1 parallel to $R_2+R_3+R_4$, and so on in this way until S_4. S_5 is equivalent to R_1+R_2 parallel to R_3+R_4 and S_6 is equivalent to R_1+R_3 parallel to R_2+R_4. The equivalent resistances were measured between points A and B for S_1, and so on in this way until S_4.,The equivalent resistances were further measured between points A and C for S_5 and between points B and D for S_6.

The corresponding equations are:

$$S_1 = R_1 \,||\, (R_2+R_3+R_4) = \frac{R_1(R_2+R_3+R_4)}{R_1+R_2+R_3+R_4} \qquad \text{Eq. 8}$$

$$S_2 = R_2 \,||\, (R_1+R_3+R_4) = \frac{R_1(R_2+R_3+R_4)}{R_1+R_2+R_3+R_4} \qquad \text{Eq. 9}$$

$$S_3 = R_3 \,||\, (R_1+R_2+R_4) = \frac{R_3(R_1+R_2+R_4)}{R_1+R_2+R_3+R_4} \qquad \text{Eq. 10}$$

$$S_4 = R_4 \,||\, (R_1+R_2+R_3) = \frac{R_4(R_1+R_2+R_3)}{R_1+R_2+R_3+R_4} \qquad \text{Eq. 11}$$

$$S_5 = (R_1+R_2) \,||\, (R_3+R_4) = \frac{(R_1+R_2)(R_3+R_4)}{R_1+R_2+R_3+R_4} \qquad \text{Eq. 12}$$

$$S_6 = (R_1+R_3) \,||\, (R_2+R_4) = \frac{(R_1+R_3)(R_2+R_4)}{R_1+R_2+R_3+R_4} \qquad \text{Eq. 13}$$

The aim of this model is to find equations for R_1 - R_4 that only depend on the equivalent resistances. Hence, in a first step Eq. 12 and Eq. 13 were solved for R_4. The outcome is shown in the equations Eq. 14 and Eq. 15.

$$R_4 = \frac{R_3S_5 + R_1(S_5-R_3) + R_2(S_5-R_3)}{R_1+R_2-S_5} \qquad \text{Eq. 14}$$

$$R_4 = \frac{R_3S_6 + R_1(S_6-R_2) + R_2(S_6-R_2)}{R_1+R_3-S_6} \qquad \text{Eq. 15}$$

$$R_3 = \frac{R_1^2 - R_2^2 - 2R_1S_5 - (R_1+R_2)\sqrt{R_1^2+2R_1R_2+R_2^2-4R_1S_6-4R_2S_6+4S_5S_6}}{2(S_5-R_1-R_2)} \qquad \text{Eq. 16}$$

$$R_3 = \frac{R_1^2 - R_2^2 - 2R_1S_5 + (R_1+R_2)\sqrt{R_1^2+2R_1R_2+R_2^2-4R_1S_6-4R_2S_6+4S_5S_6}}{2(S_5-R_1-R_2)} \qquad \text{Eq. 17}$$

In order to eliminate R_4, Eq. 14 and Eq. 15 were set equal to each other and subsequently solved for R_3 subsequently. The interim result for R_3 is represented by equations Eq. 16 and Eq. 17.

In the next step, Eq. 9 was solved for R_2 (see Eq. 18).

$$R_2 = \frac{R_1S_2 + R_3S_2 + R_4S_2}{R_1+R_3+R_4-S_2} \qquad \text{Eq. 18}$$

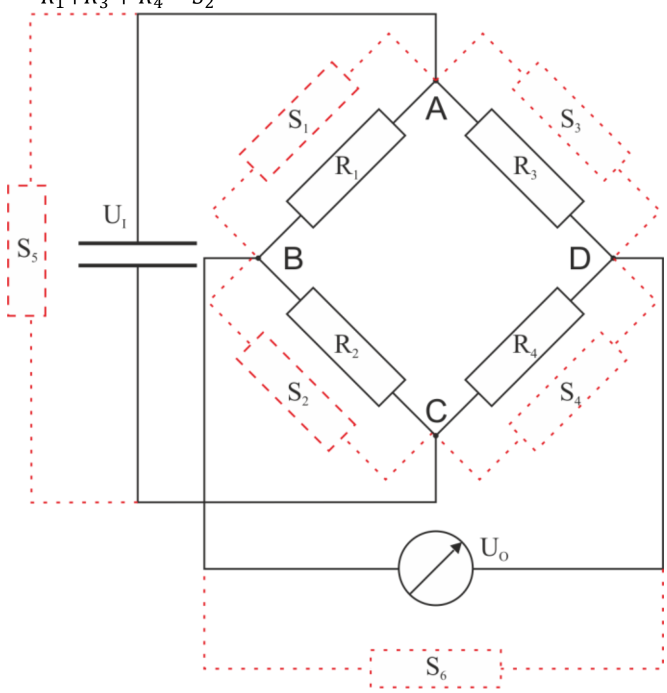

Fig. 8: Wheatstone bridge with equivalent resistances

After applying the interim results of R_3 and R_4 to Eq. 18 the equation was simplified. This leads to the interim result of R_2, represented by Eq. 19 and Eq. 20.

$$R_2 = \frac{-R_1^2 + 2R_1S_2 - R_1\sqrt{R_1^2 + 4S_2S_5}}{2(R_1 - S_2 + S_5)} \quad \text{Eq. 19}$$

$$R_2 = \frac{-R_1^2 + 2R_1S_2 + R_1\sqrt{R_1^2 + 4S_2S_5}}{2(R_1 - S_2 + S_5)} \quad \text{Eq. 20}$$

Finally, the interim results of R_2, R_3 and R_4 were applied to Eq. 21 which was obtained by solving Eq. 8 for R_1. Another simplification leads to the equation for R_1 shown in Eq. 22. This equation only depends on equivalent resistances.

$$R_1 = \frac{R_2S_1 + R_3S_1 + R_4S_1}{R_2 + R_3 + R_4 - S_1} \quad \text{Eq. 21}$$

$$R_1 = \frac{S_1^2 + (S_2 - S_5)^2 - 2S_1(S_2 + S_5)}{2(S_1 - S_2 - S_5)} \quad \text{Eq. 22}$$

Reapplying this result to the Eq. 19 and Eq. 20 leads to an equation for R_2 which only consists of equivalent resistances. This is shown in Eq. 23.

$$R_2 = -\frac{S_1^2 + (S_2 - S_5)^2 - 2S_1(S_2 + S_5)}{2(S_1 - S_2 + S_5)} \quad \text{Eq. 23}$$

The solutions for R_3 and R_2 were deduced from the symmetry of the Wheatstone bridge. They are represented by Eq. 24 and Eq. 25.

$$R_3 = \frac{S_3^2 + (S_4 - S_5)^2 - 2S_3(S_4 + S_5)}{2(S_3 - S_4 - S_5)} \quad \text{Eq. 24}$$

$$R_4 = -\frac{S_3^2 + (S_4 - S_5)^2 - 2S_3(S_4 + S_5)}{2(S_3 - S_4 + S_5)} \quad \text{Eq. 25}$$

5. Conclusions & Outlook

With the presented method, it is possible to calculate all single resistance values. The balancing of the bridge therefore becomes possible. Currently, several technologies to trim resistors are known. Two examples are shown in Fig. 9. Thin film resistors are often made of CrSi, CrNi, Ta_2N or a variety of other materials which are selected based on application specific parameters such as temperature coefficient, long term stability and noise ratio. A Nd:YAG laser can be used to change the resistance value [VOE06].

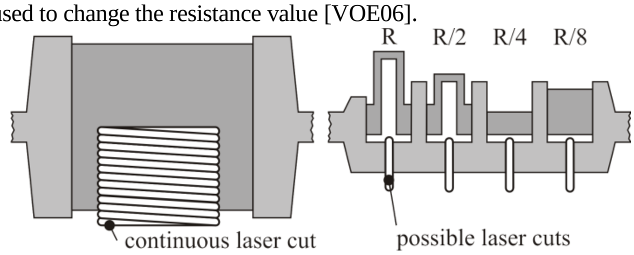

Fig. 9: Laser trimming of thin film resistors

On the left side of Fig. 9 a laser is used to continuously cut and reduce the width of the resistor to the desired value. On the right side, the laser is used to cut the conducting path at discrete positions. This example enables 16 specific values between 0 (no cut) and $1\,{}^{1}/_{8}\,R$ (four cuts).

The advantage of temperature compensation of the full bridge may be affected by this method. The trimmed resistors must have the same temperature coefficient as silicon to enable this feature. If not, the increased gain factor will still compensate for this loss.

Electrical balancing methods are also available and separating electronics from chips has many advantages. For example, if there is an offset introduced by packaging, this method cannot reduce them. This can only be done by external electronics. This method is much more flexible and easy to implement. Because this method allow piecewise handling, as well as the fact that the measuring and trimming processes cannot be performed in batch, the cost and time effort is high, but electronic complexity can be reduced.

The presented method shows potential for sensor array production, where many sensors are placed on one chip [KRA10]. The trimming method could therefore enable new sensor concepts and increase yield significantly. Automated measuring and trimming is possible with a simple 2D table laser equipped resistance measurement tools.

ACKNOWLEDGEMENT

This work was funded by the German Research Foundation in the framework of the collaborative research center 880 “Fundamentals of High Lift for Future Civil Aircraft” and by the Ministry for Science and Culture of Lower Saxony.

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