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The continuous spinning current (CSC) stress sensor method for the extraction of two stress components in an offset compensated manner

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Abstract

This paper reports on a novel method to extract two independent stress components from a single sensor with four peripheral contacts. The stress dependent signals are temperature compensated to first order and separated from other undesired signal contributions using the Fourier transform. To date, such results have been obtained only using two separate four-contact structures, e.g., Wheatstone bridges of piezoresistors and piezo-FETs, or using structures with a larger number of contacts. Similar to the continuous spinning current (CSC) method for Hall devices, the method applies a continuously spinning current to a silicon n- or p-well device. It permits to (i) extract both $\sigma_{xx} - \sigma_{yy}$ and σ_{xy} stresses; (ii) separate the stress dependent signals from other undesired signals, such as Hall voltages, thermoelectric voltages, and temperature dependent effects; and (iii) to integrate four-contact stress sensors into mixed signal systems without further means to compensate the offsets due to the amplifier and A/D conversion stages. Further, the approach is also applicable to nonlinear devices. The method has been verified with two separate four-contact sensors rotated by 45°.

Keywords: Spinning current; Fourier transform; Hall sensor; Stress sensor; Switching current; Continuous spinning current (CSC); Stress sensor method

1. Introduction

Devices capable of sensing mechanical stress are an important part of many commercially available microelectromechanical systems (MEMS) such as pressure sensors and gyroscopes [1–3]. Often, the implementation of such sensors is achieved with piezoresistive elements, i.e., simple silicon diffusions with two contacts [4]. These devices exploit the longitudinal piezoresistive effect [5]. For sufficiently small stress levels, the resistance of piezoresistors varies linearly with applied normal stresses [6]. The measurement of mechanical stress with simple piezoresistive devices is limited by the magnitude of other resistance changes and voltage contributions arising, e.g., due to temperature changes and thermal gradients [1–7].

To eliminate the strong influence of the temperature dependence of the resistance, these elements are configured as four-contact structures, e.g., Wheatstone bridges, sensors with additional contacts perpendicular to the current direction [8], or sensor rosettes [4]. Depending on their orientation, these sensor structures are capable of measuring either the $\sigma_{xx} - \sigma_{yy}$ or σ_{xy} stress component in the sensor plane.

To eliminate other signal inducing effects and measure more than one stress component with one sensor structure, more elaborate sensor concepts are necessary. We have presented improved stress sensing devices eliminating some of the shortcomings of these devices, e.g., the separation of the mechanical signal from other undesired effects, the extraction of more than one stress component, and the measurement of locally resolved stress distributions [9,10]. As an example, the device shown in Fig. 1 has eight contacts and exploits the stress dependent characteristics of monocrystalline silicon [9]. The current is switched in eight discrete directions, while the voltage parallel and orthogonal to the current direction is measured. With the novel method first presented in [11] this approach is taken a step further by applying a continuously spinning current (CSC) instead of switched spinning current to a four-contact device. This approach is similar to the CSC method

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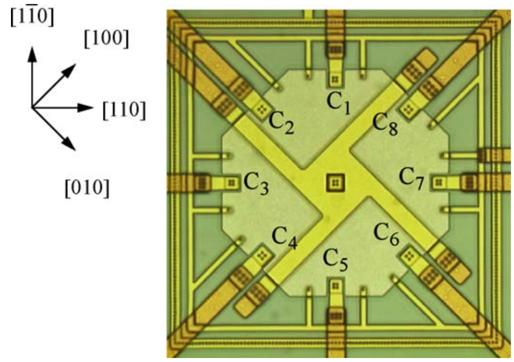

Fig. 1. Optical micrograph of an octagonal eight contact n-well stress sensor [9] permitting to extract of extracting more than one stress component in a offset compensated manner.

for Hall devices [12]. To date, four-contact devices were not capable of extracting both $\sigma_{xx} - \sigma_{yy}$ and σ_{xy} in a compensated manner.

2. Sensor operation and theory

2.1. Sensor theory

The sensor exploits the piezoresistive characteristics of (1 0 0) silicon. Consider a symmetrical planar sensor in the (1 0 0) plane, with four contacts C_1–C_4 as illustrated in Fig. 2. The contact pair axis C_1–C_3 is oriented at an angle φ with respect to the [1 1 0] direction defining the x-axis, while the C_2–C_4 contact pair axis is orthogonal to the C_1–C_3 axis. Applying a current I between C_1 and C_3 results in two measurable voltage components [9,12]. First, the longitudinal voltage $V_{||}(\varphi) = V_1 - V_3$ parallel to the current is measured between C_1 and C_3; second a transverse voltage $V_\perp(\varphi) = V_2 - V_4$ is measured between C_2 and C_4. These voltages are [9,12]

$$V_{||}(\varphi) = V_{0||}[1 + \tfrac{1}{2}F_1(\pi_{11} + \pi_{12})(\sigma_{xx} + \sigma_{yy}) + F_1\pi_{12}\sigma_{zz} + \tfrac{1}{2}F_2\pi_{44}(\sigma_{xx} - \sigma_{yy})\cos(2\varphi) + F_2(\pi_{11} + \pi_{12})\sigma_{xy}\sin(2\varphi)] \quad (1)$$

and

$$V_\perp(\varphi) = V_{0||}F_3[(\pi_{11} - \pi_{12})\sigma_{xy}\cos(2\varphi) - \tfrac{1}{2}\pi_{44}(\sigma_{xx} - \sigma_{yy})\sin(2\varphi)], \quad (2)$$

where $V_{0||}$, F_i ($i = 1, \ldots, 3$), π_{ij}, and σ_{ij} denote the longitudinal voltage in the absence of stress, geometry dependent numerical correction factors, the piezoresistive coefficients, and the components of the mechanical stress tensor, respectively.

These relations have been taken advantage of in a sensor with four contact pairs [9]. By switching the current in eight directions, it was shown that it is possible to separate the stress dependent signals proportional to $\sigma_{xy}\cos(2\varphi)$ and $(\sigma_{xx} - \sigma_{yy})\sin(2\varphi)$ from nonmechanical transverse voltages that exhibit different angular dependences. These nonmechanical signals are thermoelectric voltages, the Hall voltage, and signals due to an inhomogeneous doping concentration. In view of Shannon's theorem [14] and symmetry considerations, more than two contact pairs are necessary to measure σ_{xy} and $\sigma_{xx} - \sigma_{yy}$. In Hall sensing devices, where basically the φ-independent component of $V_\perp(\varphi)$ is measured, this limitation inspired the introduction of the CSC method for semiconductor Hall devices [12,13].

2.2. The CSC stress sensing method

A spinning current $I(\phi)$ is induced in the four-contact device by superposing two orthogonal currents (a) $I_{13} = I_0\cos(\phi)$ and (b) $I_{24} = I_0\sin(\phi)$ as shown in Fig. 3. Each of these current contributions taken separately corresponds to voltage drops $V_{13} = V_1 - V_3$ and $V_{24} = V_2 - V_4$ across the device. In the case of the current I_{13} these are

$$V_{13}^{a}(\phi) = V_{0||}\cos(\phi)[1 + \tfrac{1}{2}F_1(\pi_{11} + \pi_{12})(\sigma_{xx} + \sigma_{yy}) + F_1\pi_{12}\sigma_{zz} + \tfrac{1}{2}F_2\pi_{44}(\sigma_{xx} - \sigma_{yy})\cos(2\varphi) + F_2(\pi_{11} - \pi_{12})\sigma_{xy}\sin(2\varphi)], \quad (3)$$

$$V_{24}^{a}(\phi) = V_{0||}F_3\cos(\phi)[(\pi_{11} + \pi_{12})\sigma_{xy}\cos(2\varphi) - \tfrac{1}{2}\pi_{44}(\sigma_{xx} - \sigma_{yy})\sin(2\varphi)]. \quad (4)$$

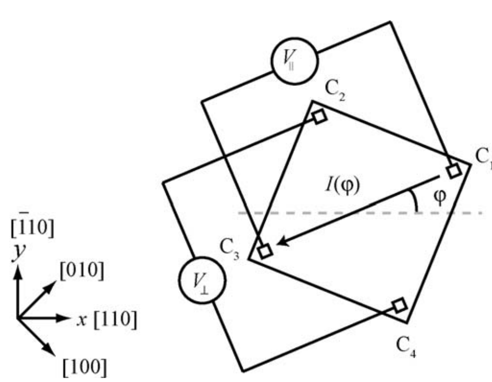

Fig. 2. Schematic illustration of a four-contact silicon sensor oriented at an arbitrary angle φ with respect to the [1 1 0] x-axis.

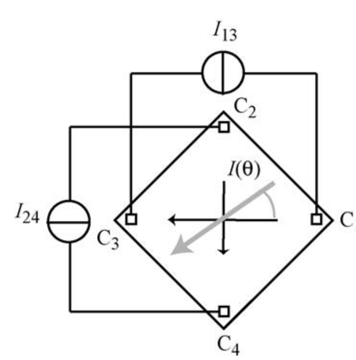

Fig. 3. Schematic illustration of a spinning current resulting from two superposed currents $I_{13} = I_0\cos(\phi)$ and $I_{24} = I_0\sin(\phi)$.