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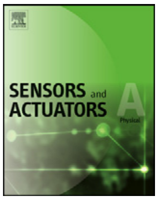

Piezoresistive CMOS-compatible sensor for out-of-plane shear stress

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ABSTRACT

A piezoresistive CMOS-compatible sensor for measuring the temperature-compensated out-of-plane shear stress components σ_{xz} and σ_{yz} is analyzed, implemented, and applied. The device exploits the shear piezoresistive effect due to vertical (out-of-plane) shear stress components. Possible sensor geometries are discussed and sensitivity considerations based on an affine transformation are presented. A bi-directional, 53 μm × 53 μm-large sensor design measuring two output voltages linearly proportional to the vertical shear stress components σ_{xz} and σ_{yz} is introduced. The experimental characterization of 17 such structures revealed an offset of the measurement voltage of -1.3 ± 0.6 mV and a linear sensitivity of -320 ± 85 μV/MPa. A variation of the supply voltage from 0 V to 5 V modulates the sensor resistance and voltage-related sensitivity by +6% and −12%, respectively. The geometry dependence of the sensitivity is evaluated using a finite element analysis. Design guidelines are extracted from these simulations. A demonstration of the sensor performance in an application concludes this paper.

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1. Introduction

Mechanical stress sensors based on the piezoresistive effect in silicon are valuable and widely used tools for mechanical sensing [1,2]. This is especially true for the in situ measurement of mechanical stresses in die packages [3–10]. Furthermore, the combination of low-*k* materials with copper, the continuing reduction of the die thickness, and the legislative requirement of lead-free solder alloys pose new challenges regarding interconnect reliability [11,12]. In this context, knowledge of the stress state within the packages and at the surface of the encapsulated silicon chip is crucial for optimizing the package stability.

To minimize the interfacial (out-of-plane) stresses in the die surface close to the interlayer dielectrics, in situ measurements of the out-of-plane shear stresses are of particular interest [13]. In the area of microelectronic packaging, a large effort has been dedicated to quantify stresses in packages using methods such as simulation [14–16], X-ray topography [14], electrical impedance tomography [17], and piezoresistive measurements using (1 1 1) silicon [18,19].

The interest in the out-of-plane shear stress components originates from the need to quantitatively understand the failure processes in die packages, e.g., in ball grid arrays, where the vertical stress components are expected to be a major reason for device failure [15,20,21]. Furthermore, experimental stress data are a prerequisite for validating numerical simulations of complex material compounds [22,23]. Mechanical stress components in this paper refer to the following *xyz* coordinate system: the out-of-plane *z* direction points in the [0 0 1] crystal direction perpendicular to the wafer plane, while the *x* and *y* axes coincide with [1 1 0] and $[\bar{1}\,1\,0]$ crystal directions, respectively. We make this choice based on the fact that edges of diced chips are usually parallel to the [1 1 0] and $[\bar{1}\,1\,0]$ directions.

Until recently, CMOS-based piezoresistors have featured only in-plane current components. This restriction limits the accessible stress information to the temperature compensated in-plane shear stress components σ_{xy} and $\sigma_{xx} - \sigma_{yy}$ [24,25] and temperature-uncompensated stress values of σ_{xx}, σ_{yy}, and σ_{zz} [26]. The two in-plane shear stress components can be measured accurately using diffused resistors with different orientations [3,26], pseudo-Hall sensors in diffused wells [27–29], and inversion layers [10]. The normal stress components as well as the temperature change ΔT can in principle be extracted from three additional independent resistance measurements [26]. In practice, uncertainties in the involved piezoresistive coefficients, thermal coefficients of resistance, and temperature lead to large uncertainties in the extracted individual normal stress components [30]. One of the limiting factors in the extraction of the out-of-plane stress components using established sensors was the restriction to in-plane currents. Vertical current components offer additional options to measure the state of mechanical stress in the material [17]. A sensor exploiting the piezoresistive effect on vertical current components, sensitive to the normal stress sum $(\sigma_{xx} + \sigma_{yy})/2 - \sigma_{zz}$, has recently been presented [31,32].

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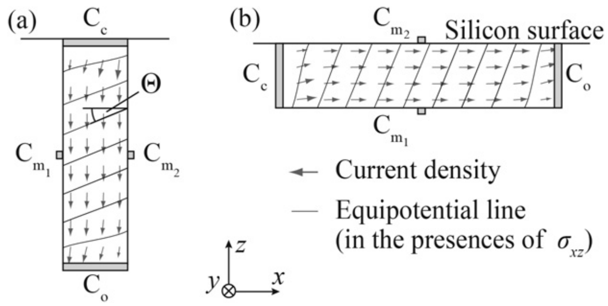

Fig. 1. Hypothetical sensor structures with buried contacts enabling the shear piezoresistive effect on (a) vertical and (b) horizontal currents caused by σ_{xz} to be detected. The equipotential lines are distorted by a vertical shear stress σ_{xz} = 200 MPa and the arrows indicate the current density distribution.

A second type of CMOS-integrated vertical stress sensor exploiting vertical current components is presented in this paper. It is termed vertical shear stress sensor (VSSS). The shear piezoresistance effect acting on vertical current components provides independent information on the local stress state. It allows the two vertical shear stress components σ_{xz} and σ_{yz} to be extracted in an inherently temperature-compensated manner. First sensor designs and application examples have been presented previously [8,33–36]. This paper provides a significantly more detailed analysis of the device.

2. Sensing principle

The following argument focuses on the detection of the vertical shear stress component σ_{xz}. In view of the crystal symmetry, analogous mechanisms are effective for the detection of σ_{yz} after rotation of the design by $\pi/2$ around the z-axis.

In a (0 0 1) silicon wafer, σ_{xz} modulates only the resistivity tensor component ρ_{xz} [26]. Assuming σ_{xz} to be the only stress component in the material, the resulting anisotropic resistivity tensor is then

$$\boldsymbol{\rho}(\sigma_{xz}) = \rho_0 \begin{pmatrix} 1 & 0 & \pi_{44}\,\sigma_{xz} \\ 0 & 1 & 0 \\ \pi_{44}\,\sigma_{xz} & 0 & 1 \end{pmatrix}, \qquad (1)$$

where ρ_0 and π_{44} denote, respectively, the isotropic resistivity in the stress-free state and the shear piezoresistance coefficient of silicon. For weakly p-doped silicon, such as a CMOS p-well, π_{44} takes the value $138 \times 10^{-11}\ \mathrm{Pa}^{-1}$ [37]. Eq. (1) is valid for all coordinate systems resulting from rotations of the xyz coordinate system around the z-axis.

Since $\boldsymbol{\rho}$ connects the current density vector $\boldsymbol{j}$ and the electric field vector $\boldsymbol{E}$ via $\boldsymbol{E} = \boldsymbol{\rho}\,\boldsymbol{j}$, it is easily seen that only the components of $\boldsymbol{j}$ and $\boldsymbol{E}$ in the xz plane are affected in their relationship. As a consequence, σ_{xz} at a location $\boldsymbol{r}$ can be determined by measuring the local $\boldsymbol{E}(\boldsymbol{r})$ relative to $\boldsymbol{j}(\boldsymbol{r})$ in the xz plane. In particular, the action of the piezoresistive effect on the current density $j_z(\boldsymbol{r})$ measured via $E_x(\boldsymbol{r})$ and on $j_x(\boldsymbol{r})$ measured via $E_z(\boldsymbol{r})$ potentially provide information on σ_{xz} at the position $\boldsymbol{r}$. Explicitly, the corresponding relationships are

$$E_x(\boldsymbol{r}) = j_x(\boldsymbol{r})\,\rho_0 + j_z(\boldsymbol{r})\,\rho_0\,\pi_{44}\,\sigma_{xz} \qquad (2)$$

and

$$E_z(\boldsymbol{r}) = j_x(\boldsymbol{r})\,\rho_0\,\pi_{44}\,\sigma_{xz} + j_z(\boldsymbol{r})\,\rho_0. \qquad (3)$$

Two hypothetical sensor designs featuring dominantly vertical and horizontal current between two contacts C_c and C_o are shown in Fig. 1(a) and (b), respectively. The distortion of the equipotential lines induced by the shear stress σ_{xz} results in the detectable voltage difference V_m between point-like measurement contacts C_{m_1} and C_{m_2} located on both sides of the current flow. Similarly to the definition of the Hall angle in magnetic sensors, the pseudo-Hall angle Θ is defined between the electric field vectors, and thus the equipotential lines, in the stressed and stress-free states.

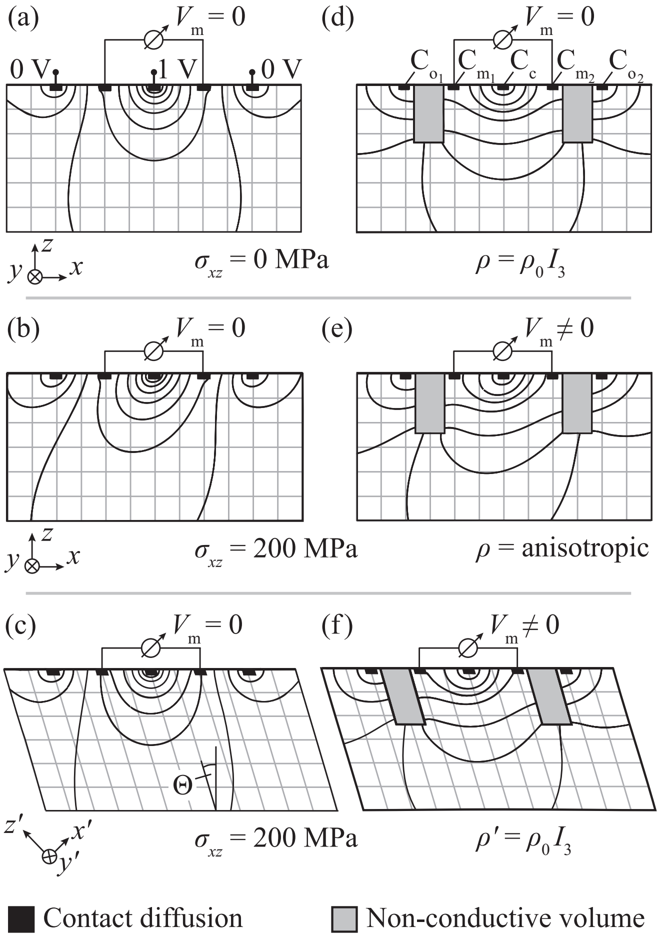

Fig. 2. CMOS compatible five-contact sensors (a and d) in the stress-free state featuring an isotropic resistivity. (b and e) The same sensor geometries under the stress σ_{xz} = 200 MPa and (c and f) in the stressed state after an affine transformation to a coordinate system corresponding to an isotropic resistivity.

Unfortunately, electrical contacts buried below the silicon surface are challenging to realize and not available in standard CMOS technology. However, a similar challenge has been solved for vertical Hall sensors [38,39], resulting in five-contact device as shown in Fig. 2(a), where the current contact C_o is split into two separate outer contacts C_{o_1} and C_{o_2}, resulting in five contacts equidistantly placed on the silicon surface along the x-axis. A supply voltage is applied between the center contact C_c and these two outer contacts, while the voltage difference V_m is measured between C_{m_1} and C_{m_2}. The symmetric potential distribution in the stress-free state is shown in Fig. 2(a). The equipotential lines in this plot were extracted from two-dimensional numerical simulations using the standard *AC/DC module* of *COMSOL Multiphysics*, with the electrical potentials defined in a p-type silicon substrate with homogeneous resistivity.

However, the sensor design is stress-insensitive as demonstrated in Fig. 2(b), where an anisotropic resistivity caused by a stress σ_{xz} = 200 MPa has been assumed. Although the equipotential lines are clearly influenced by the mechanical stress, no potential difference is found between the measurement contacts. This can be understood easily by applying an appropriate affine

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