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Evaluation of p-type polysilicon piezoresistance in a full-bridge circuit for surface stress sensors

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ABSTRACT

The evaluation of p-type polycrystalline silicon (polysilicon) piezoresistance in a full-bridge circuit is proposed for the application of surface stress sensors. With a simple four-point bending technique, the longitudinal and transverse gauge factors (GFs) of p-type polysilicon are determined to be 35 and -10, respectively. Further, the full-bridge circuit composed of longitudinal and transverse piezoresistors can improve the sensing sensitivity through a p-type shear piezoresistive coefficient. Then, the full-bridge voltage noise spectra show that the $1/f$ form is the dominant noise source in low-frequency regimes. From the linear relationship between the low-frequency $1/f$ noise and full-bridge excitation voltages, a low Hooge constant α_H of 6×10^{-5} is obtained. An increase in the offset voltage with an increase in temperature is measured from the output signal at a balanced full-bridge circuit, which can be attributed to the mismatch of the temperature coefficient of the sensing piezoresistors. Finally, under the needle force probing in the surface stress sensor platform, the piezoresistive responses of the full-bridge output voltage as a function of time are achieved.

1. Introduction

The piezoresistance (PZR) effect in silicon (Si) was discovered by Smith in 1954 [1]. Owing to the excellent electromechanical properties of Si and the availability of integrated-circuit-compatible CMOS processes [2], the Si PZR effect has been widely used in many sensor applications such as pressure sensors [3], accelerometers [4,5], and biological sensors [6]. In general, the PZR effect is created by the modification of energy band structures by applied strain, thereby leading to changes in the effective mass, mobility, and conductivity [7]. The gauge factor (GF) is used to characterize the PZR sensitivity; GF is defined as the ratio of the normalized change in Si resistivity to the applied strain ε. For a single-crystal Si in certain directions, such as the $\langle 110 \rangle$ direction, the GF lies between 50 and 100. Similarly, the discovery of the PZR effect in polycrystalline Si (polysilicon) in the 1970s [8,9] facilitates its sensing applications [10,11]. The polysilicon as a piezoresistive material instead of the single-crystalline Si offers the advantages of low cost, ease of processing, and good thermal stability, and p–n junction isolation is not necessary even though its GF value is lowered. Recently, Yoshikawa et al. [12] demonstrated that a cantilever-type surface stress sensor with four single-crystalline Si-sensing piezoresistors showed enhanced sensitivity as compared to conventional reported cantilever sensors [13–15]. To the best of our knowledge, current understanding regarding the evaluation of p-type polysilicon PZR in a full-bridge circuit for cantilever-type surface stress sensors, as shown in Fig. 1, is still poor.

Therefore, the study focused on the evaluation of p-type polysilicon as a piezoresistive material. Four polysilicon

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piezoresistors, which are embedded into the four sensing beams of a cantilever-type surface stress sensor (Fig. 2a), can comprise a full-bridge circuit (Fig. 2b). From the relationship between the resistivity and the applied strain ε, the PZR properties and GF value of the polysilicon can be substantially increased and obtained. Simultaneously, the low-frequency voltage noise spectra and temperature coefficient of the sensing piezoresistors are extracted. Finally, the piezoresistive responses of the cantilever-type sensor platform are validated.

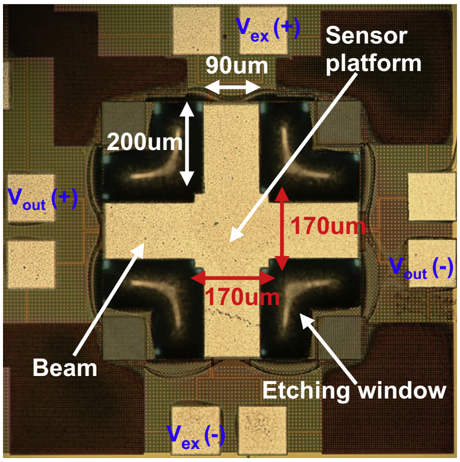

Fig. 1. Optical microscope view of a cantilever-type surface stress sensor suspended by four sensing beams.

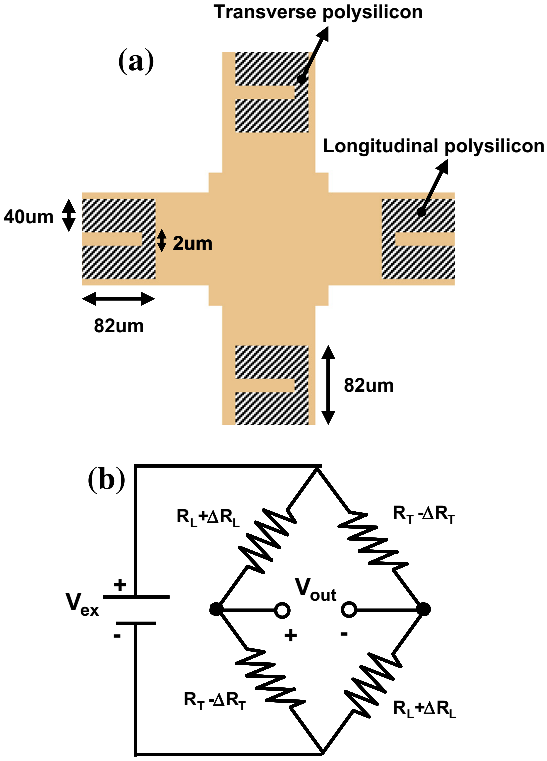

Fig. 2. (a) Schematic illustration of the cantilever-type sensor platform having four sensing piezoresistors. (b) Four polysilicon piezoresistors embedded into the sensing beam comprising a full-bridge circuit.

2. Sensor microstructure fabrication and measurement

The cantilever-type surface stress sensors were fabricated using a standard TSMC 1P6M 0.18-μm CMOS–MEMS process. After the completion of this CMOS process, a clear tone PAD mask was defined to pre-strip the passivation above the microstructure, as shown in Fig. 3a. For the post-micromachining process, a clear tone RLS mask was utilized to pattern the photoresist (PR). Then, the area without PR protection was subjected to both anisotropic SiO_2 dry etching (Fig. 3b) and isotropic Si substrate wet etching (Fig. 3c). The final sensor microstructure was released by isotropic Si substrate wet etching. The optical microscope view of the cantilever-type sensor platform was shown in Fig. 1. To further obtain the PZR properties, we designed two test keys of U-shape polysilicon along the longitudinal or transverse directions, as shown in Fig. 4a, in the CMOS process region. A simple four-point bending technique (4PB) was employed to supply a uniform uniaxial strain to the p-type polysilicon piezoresistor. The magnitude of the uniaxial strain can be directly obtained through the strain gauge mounted on a wafer strip. The detailed strain measurement had been published elsewhere [16]. The full-bridge voltage noise spectral density (S_V) was measured at room temperature by using a low-noise amplifier SR560 and a National Instruments PCI-4461 spectrum analyzer with different dc excitation voltages (V_{ex}). The noise frequency ranged from 10 Hz to 100 kHz. Finally, all electrical measurements were carried out using a Keithley 2400 source meter.

3. Results and discussion

3.1. Longitudinal and transverse GF

From the current versus voltage measurements on two test keys (Fig. 4a) of the p-type U-shape polysilicon, the resistance value of two piezoresistors is determined to be 2 kΩ regardless of the longitudinal or transverse directions. Based on the above 2 kΩ piezoresistor and the dimensions of the polysilicon (Fig. 2a), the p-type concentration can be estimated to be approximately $1 \times 10^{19}\ \mathrm{cm}^{-3}$. Further, the GF is expressed as

$$\mathrm{GF} = \frac{\Delta\rho/\rho}{\Delta\varepsilon}, \tag{1}$$

where $\Delta\rho/\rho$ is the normalized change of the polysilicon resistivity, and ε is the applied strain. Fig. 4b shows the normalized resistivity change of the p-type polysilicon dependence on the applied strain for the extraction of the GF value. The longitudinal GF (donated by GF_L) and the transverse GF (donated by GF_T) values are determined to be 35 and −10, respectively. The measured GF values at a concentration of $1 \times 10^{19}\ \mathrm{cm}^{-3}$ lie within the theoretical calculation range of the p-type polysilicon [17], further implying that the 4PB technique is applicable to the