Mechanics of Flexible and Stretchable Strain Gauges Based on Si Nanomembranes

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ABSTRACT: Single crystalline Si is well known for its high piezoresistivity for strain sensing. Its applications are limited by demanding processing conditions and the stiff and brittle nature of Si. We have developed strategies that avoid these limitations, to allow ultrathin (~100 nm) single crystalline Si resistors and Wheatstone bridges for strain sensing on thin, flexible sheets of plastic, or slabs of rubber, with the ability for high speed, spatial mapping of distributions of strain, in multiplexed arrays. Tensile and bending experiments reveal gauge factors as high as 43. Because of the huge elastic mismatch between Si (E_{Si} = 165 GPa) and polymer substrates (as soft as E_{sub} = 60 kPa), mechanics approaches such as shear lag models and finite element analysis are used to study the effects of elastic mismatch and Si geometry on the gauge factor of the flexible or stretchable strain sensing device.

INTRODUCTION: The discovery of piezoresistive effects in silicon by Smith in 1954 [1] led to the development of classes of silicon-based electromechanical sensor technologies [2, 3]. Single-crystalline silicon exhibits substantially high piezoresistive effects compared to metal or amorphous or polycrystalline Si [4]. Large piezoresistive coefficients, high natural abundance, and mature processing technologies represent attractive aspects of silicon for these applications. Typically, silicon-based sensors are fabricated on wafers and then subsequently diced and integrated into small packages with microelectronic integrated circuits for signal manipulation and recording [2, 3]. Although well configured for many applications, devices in this form are incompatible with certain applications in structural health monitoring for aircraft and in interfaces to the human body, where large-area large-scale integrated networks of sensors on thin deformable substrates are required. In this paper, we report materials, integration strategies, mechanical modeling results, and system demonstrations of distributed networks of piezoresistive strain sensors based on ultrathin single-crystalline silicon membranes bonded to thin polymer substrates such as polyimide and elastomer. Such systems offer strain sensitivity, i.e. gauge factor (GF), while providing lightweight construction and mechanical flexibility or even stretchability. By using Wheatstone bridge (WB) configurations for the sensors and coupling them to multiplexing diodes, this technology can be scaled to large-area integrated monitors with spatial mapping capabilities.

RESULTS: The integration of Si nanomembranes on polymer substrates starts with derive silicon nanomembranes (which we refer to as microstructured silicon, or μs-Si) from bulk wafers, or silicon-on-insulator (SOI) substrates, and then assembled using printing-like techniques onto thin sheets of polyimide or silicone rubber [5]. Membranes are then patterned into strips and WB and are interconnected by stretchable metal wires. Figure 1(a) shows the measured resistance of polyimide-bonded Si nanostrips linearly varies with tensile strain throughout. The effective GF of this heterogeneous system is ~43 derived by $GF = \Delta R/R/\varepsilon_{app}$, where ε_{app} is the applied strain onto the substrate. Because of the finite size of the Si strip and the mechanical mismatch between Si and polymer, the *GF* measured in this manner does not directly yield the value for the single crystalline Si can be analytically calculated by the following equation [6]: $GF_{Si} = \alpha \cdot \pi_{Si} \cdot E_{Si} = 97$, where α is a correction coefficient accounting for different doping concentrations [7], π is the piezoresistive coefficient, and E represents Young's modulus. An analysis by finite-element modeling (FEM) yields intrinsic strain in Si ε_{Si} = 0.045% at an applied strain ε = 0.1%. The effective system *GF* can be then estimated by $GF = GF_{Si} \cdot \varepsilon_{Si}/\varepsilon_{app} = 43$, which is in excellent agreement with the measurement. Fig. 2(b) shows the change in the output voltage of a WB strain gauge under 3 V input bias as a function of applied uniaxial tensile strain. The output voltage can be predicted by $V_{out}/V_{in} = R_1/(R_1+R_2) - R_4/(R_3+R_4)$, where R denotes the resistance of each bridge under deformation. It is given by $R = R_0(1+GF\cdot\varepsilon)$, where ε is the applied strain, and R_0 is the initial resistance each bridge. These gauges are sensitive to both in-plane and bending strains, as demonstrated in Fig. 1(c).

A very unique application of Si strain gauges built on thin skin-like elastomer substrate is the integrated with biological tissues. Figure 2 illustrates an array of Si strain rosettes supported by a 0.3-mm-thick elastomer sheet whose modulus matches with biological tissues. Quantification of strains associated with heart muscle under healthy and ischemia conditions clearly reveals the change in beating amplitude, as shown in Fig. 2(f).

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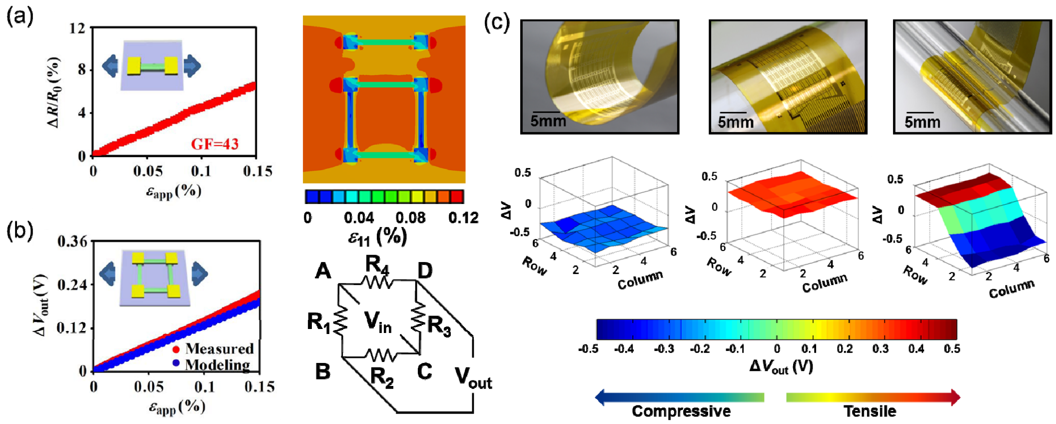

Fig. 1 (a) Fractional change in resistance ($\Delta R/R_0$) of a Si resistor as a function of the applied longitudinal tensile strain ε_{app} with corresponding FEM given horizontal ε_{app} = 10%. (b) Fractional change in output voltage (ΔV_{out}) of a WB drawn in the right frame as a function of ε_{app}. (c) Operation of the integrated array of µs-Si strain sensors under bending.

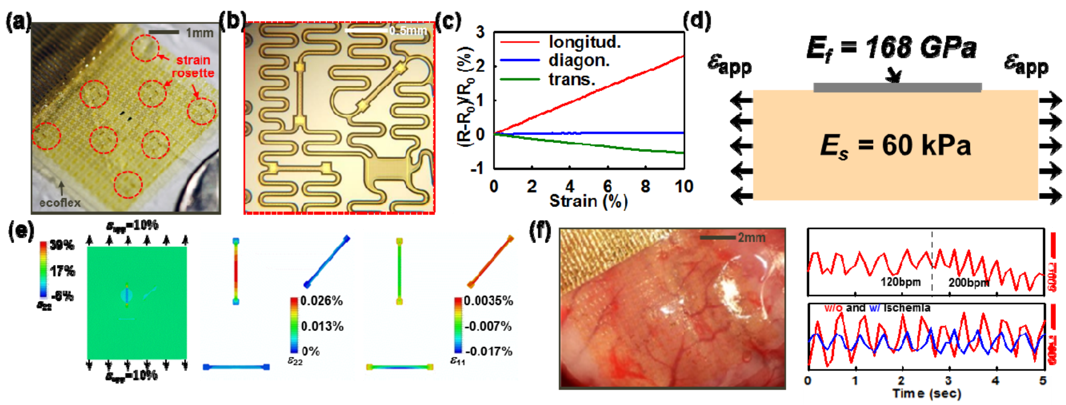

Fig. 2. (a) Optical image of array of eight stretchable strain rosettes transfer-printed on 0.3-mm thick soft silicone substrate. (b) Enlarged view of the red dotted circles in Fig. 2A showing one of eight strain rosettes with longitudinal, diagonal and transverse silicon piezoresistors. (c) Change of resistance as a function of uniaxial tensile strain for longitudinal, diagonal and transverse resistors. (d) 2D schematics of Si islands on silicone substrate. (e) Finite element modelling of silicone-supported silicon resistors under 10% applied strain. (f) in vivo test of stretchable strain gauge sheet laminated on beating rabbit heart. The measurement shows that the beating frequency is changed after pacing and the expansion amplitude is reduced after ischemia occurs.

CONCLUSIONS: High performance flexible and stretchable strain gauges can be manufactured through printing single-crystalline silicon onto compliant polymer substrates. Mechanical and electrical measurements show good stability and high sensitivity well suited for many applications in structural health monitoring and biomedical applications.

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