INTEGRATED POLYSILICON TACTILE SENSOR

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ABSTRACT

A polysilicon tactile sensor that is sensitive to tangential force has been designed, fabricated, and tested. Microfabrication of silicon is employed to create a sensor that has a linear response of 465 mV N^{-1} of tangential force over a force range of $\pm 6.25 \text{ mN}$. The minimum resolvable tangential force is $42 \text{ }\mu\text{N}$.

INTRODUCTION

The ability to sense touch is highly desirable for many robotics and manufacturing applications. In Harmon's comprehensive survey of automated tactile sensing¹, it is reported that touch sensing will become indispensable for robotic manipulation and assembly. Sensors that range from mere contact devices to highly sensitive tactile elements have been demonstrated and are commercially available for forces perpendicular to surfaces. Tangential force has proven to be more difficult to detect. Previously reported tangential force sensors have depended on polymeric interfaces to transmit the force^{2,3}. Polymer tactile sensors have hysteresis problems and long recovery times that impede their use in slip-detection feedback loops which are necessary for robotic manipulators.

Polysilicon has been demonstrated to have many advantages as a material for monolithic integrated sensors. It can be precisely micromachined to create sensor structures using conventional semiconductor-fabrication techniques⁴ and its piezoresistive⁵ and pyroresistive nature⁶ allow it to be used for sensing. These qualities are exploited in this work to create a novel tactile sensor.

DEVICE FABRICATION

Fabrication was carried out using a 4-mask process in the University of California, Berkeley EECS Microelectronics Laboratory. Figure 1 shows a perspective view of the fabricated sensor which is $2.5 \text{ }\mu\text{m}$ in width by $100 \text{ }\mu\text{m}$ in length, and $1.5 \text{ }\mu\text{m}$ in height.

The starting material is a (100) 4-inch p-type silicon wafer with a resistivity of $50 \text{ }\Omega\text{cm}$. In order to simulate an MOS compatible process, a 580 nm -

thick layer of thermal silicon dioxide is grown by wet oxidation and forms the foundation for the sensor. A $1.5 \text{ }\mu\text{m}$ -thick layer of undoped LPCVD polysilicon is deposited and patterned using standard photolithographic techniques. The polysilicon is RIE plasma-etched in a Lam plasma etcher using 95 sccm CCl_4 , 80 sccm helium , and 5 sccm oxygen at 300 watts and 240 millitorr . These conditions produce an etch rate of 375 nm/min for polysilicon, 30 nm/min for silicon dioxide, and 100 nm/min for Kodak 820 photoresist. The plasma etch results in a near vertical polysilicon sidewall. The polysilicon is then thermally oxidized in steam at 915°C for 30 minutes to provide electrical isolation and act as a diffusion barrier. A second layer of undoped LPCVD polysilicon is deposited to form the piezoresistive sensing element. The wafer is annealed at 1100°C for 120 minutes in nitrogen to increase the polysilicon grain size for optimum piezoresistivity. The wafer is ion-implanted with boron at an energy of 40 keV and a dose of $1.5 \times 10^{15} \text{ cm}^{-2}$. It is then annealed in nitrogen at 1000°C for 30 minutes to activate the implant and obtain a uniform boron concentration in the polysilicon. A MOSFET polysilicon spacer technique is used to remove polysilicon from the top of the sensor and retain the polysilicon on the sidewalls. In this technique, one micrometer of positive photoresist is spun on. The planarizing properties of the photoresist result in a thinner layer over a high step than above the rest of the wafer. Etching $0.6 \text{ }\mu\text{m}$ of the photoresist in an oxygen plasma removes it from the top of the sensor and leaves $0.4 \text{ }\mu\text{m}$ over the field. The piezoresistor polysilicon is defined in an RIE plasma etch using the steps previously described. Aluminum is sputtered for the interconnect metalization, which is patterned, wet etched, and sintered at 450°C for 15 minutes in forming gas.

THEORY

The sensor, shown in Fig. 2, forms a cantilevered beam loaded by a tangential force F applied in the x -direction which causes stress σ that increases linearly to the support end of the beam.

$$\sigma = \frac{F x y}{I} \quad (1)$$

where I is the moment of inertia and y is measured from the free end. For a rectangular structure of width w and height h_b ,

$$I = \frac{h_b w^3}{12} \quad (2)$$

Substituting Eq. 2 into Eq. 1, we find

$$\sigma = \frac{12 F x y}{h_b w^3} \quad (3)$$

To find the average stress in the sensing element on the right side of Fig. 2, we integrate the stress over the piezoresistor cross-section and divide by its area.

$$\sigma_{avg} = \frac{1}{h_a w_a} \int \sigma(x, y) dA \quad (4)$$

where h_a and w_b are the height and thickness of the piezoresistor, respectively. Solving the integral and substituting the dimensions of the sensor,

$$\sigma_{avg} = 2.5 \times 10^{-3} F \quad [N \mu m^{-2}] \quad (5)$$

The tangential force F , applies compressive stress to the right-sensing element, and an equal magnitude of tensile stress to the left-sensing element. These elements are polysilicon piezoresistors with currents flowing transverse to the direction of the stress. Therefore, the force results in an equal and opposite change in resistance of the two polysilicon resistors.

$$\frac{\Delta R}{R} = G \sigma_{avg} E^{-1} \quad (6)$$

where G is the transverse gauge factor of the polysilicon and E is the modulus of elasticity. The transverse gauge factor for polysilicon with boron doping of $5 \times 10^{19} \text{ cm}^{-3}$, that has been annealed at 1100°C for 2 hours is -13.6 . Substituting constants, the theoretical output from a half bridge, biased with 2 V, is

$$\frac{\Delta V}{F} = 465 \quad [mV N^{-1}] \quad (7)$$

RESULTS

The sensor output was measured using a half-bridge amplifier circuit in a static-test setup. The wafer was diced, mounted, and bonded to the top surface of a 40 pin DIP which was plugged into a breadboard mounted on an xy stage. A 2mm square chip from a silicon wafer was placed on an array of sensors. A microprobe loaded with weights was used to control the normal force on the silicon. The weights were suspended by a string running over a pulley and attached to the stage.

The sensor response to the tangential force is shown in Fig. 3. A linear output is observed as predicted in Eq. 7 for forces less than 300 mN loading an array of elements. For a single element the corresponding force was 6.25 mN. The calculated modulus of elasticity was $7.0 \times 10^{-2} \text{ N}/\mu\text{m}^2$ which is less than the bulk silicon value ($19 \times 10^{-2} \text{ N}/\mu\text{m}^2$).⁷

A time-varying force was applied to study the frequency response and hysteresis characteristics of the sensor. A piece of elastic was attached between the xy stage and a calibrated strobe wheel. The revolving wheel applies a varying tangential force to the stage. For a frequency of less than 5 Hz, the sensor response showed no hysteresis. At higher frequencies the testing setup proved inadequate.

CONCLUSIONS

Polysilicon has been used to build an integrated tactile sensor sensitive to tangential force. The device demonstrates high sensitivity to tangential force, and a linear output.

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Figure 3. Half Bridge Response of Sensor To Tangential Force

Figure 1. Perspective of the polysilicon sensor.

Figure 2. Cross section of the beam showing orientation of the tangential force F .