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MEASUREMENT OF FRACTURE STRESS, YOUNG'S MODULUS, AND INTRINSIC STRESS OF HEAVILY BORON-DOPED SILICON MICROSTRUCTURES

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Heavily boron-doped silicon microstructures fabricated using deep-boron diffusions and boron etch-stops have been widely used in a variety of integrated sensors and actuators. For many applications, having knowledge of the mechanical properties such as Young's modulus, intrinsic stress, and fracture stress of these films is very important in predicting the response parameters of the sensors and actuators that utilize them. These parameters include mechanical resonant frequency, sensitivity, bandwidth, linearity, and operating range. This paper describes the measurement of fracture stress, Young's modulus, and intrinsic stress of boron-doped silicon microstructures at doping concentrations above 5×10^{19} cm^{-3}. The measurement of fracture stress is performed using 15 μm thick cantilever beams of widths ranging from 20 to 150 μm. The beams were bent to fracture and the maximum fracture stress was measured to be $\approx 1.8 \times 10^{10}$ dyne cm^{-2} which is a factor of about six higher than silicon structures with larger dimensions (bulk silicon). Young's modulus and intrinsic stress were measured using a novel custom-designed doubly supported beam (bridge) structure. The measurement technique uses the characteristic pull-in voltage of the beam as electrostatic voltage is applied across an air gap capacitor in the middle of the beam, which causes the bridge to collapse. The Young's modulus for (110)-oriented silicon was measured to be $\approx (2\text{–}2.2) \times 10^{12}$ dyne cm^{-2} which is 20%–30% higher than undoped silicon. The measured intrinsic stress of 1.83×10^{8} dyne cm^{-2} agrees well with the measured pressure–deflection characteristics of thin diaphragms.

1. INTRODUCTION

Heavily boron-doped silicon microstructures fabricated using deep-boron diffusion and boron etch-stop techniques have been widely used in a variety of integrated sensors and microactuators[1–3]. These techniques offer high reproducibility, excellent uniformity, high yield, and ease of processing in fabricating a number

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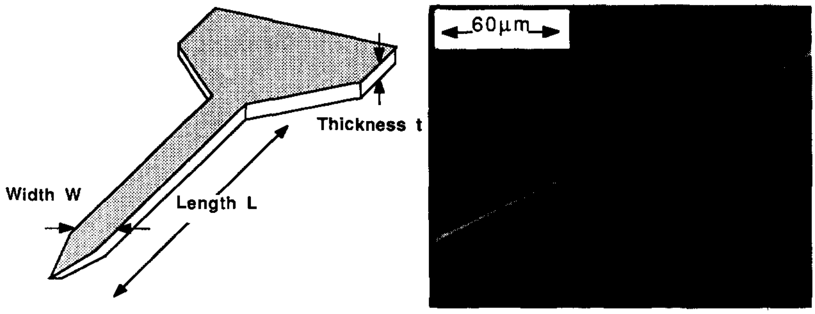
of microstructures, including diaphragms ranging in thickness from 1 to 20 μm, doubly clamped beams, and cantilever beams of various dimensions. For many applications, having knowledge of the mechanical properties such as Young's modulus, intrinsic stress and fracture stress of thin films is very important in calculating and characterizing the response parameters of sensors and actuators that utilize them. These parameters include mechanical resonant frequency, sensitivity, bandwith, linearity and operating range. For micromechanical and silicon microdynamic structures, the state of the intrinsic strain of the thin film used is also very important as this often determines the final physical shape of the microstructures that are released from their host substrate. In calculating the performance characteristics of the sensors and actuators using heavily boron-doped silicon, frequently values of mechanical properties for undoped single-crystal silicon are used instead, which result in erroneous and unrealistic calculations and simulations.

Measurement of mechanical properties of heavily boron-doped silicon has not been reported in the past. However, many techniques have been devised to measure the intrinsic stress and Young's modulus of thin films[4–7] by either visually measuring the deflection/buckling of custom designed release structures or by optically measuring the deflection of diaphragms as a function of pressure. Measurement of Young's modulus has also been performed by measurement of the resonant frequency of cantilever beams[8], as well as the pressure/deflection behavior of diaphragms and deformation of release structures. The release structures are often large and cannot be easily integrated with the sensors/actuators. In addition, certain designs for these structures are not suitable for materials with large Young's modulus[4]. The deflection and movement of the structures due to intrinsic stress after their release and the accuracy with which they can be measured is very limited and requires complicated measurement setups.

This paper reports the measurement of fracture stress. Young's modulus and intrinsic stress of heavily boron-doped silicon at doping concentrations above $5 \times 10^{19}\ \mathrm{cm}^{-3}$ using simple and accurate measurement techniques and structures. The measurement of fracture stress is performed using cantilever beams. The beams were bent to fracture and the fracture stress was then calculated by measuring the maximum tip deflection of the beam at fracture. Young's modulus and intrinsic stress were measured using a novel custom-designed doubly supported beam (bridge) structure. The measurement technique uses the characteristic pull-in voltage of the beam as electrostatic voltage is applied across an air gap capacitor in the middle of the beam, which causes the bridge to collapse. Thus, the technique only involves measurement of capacitance as a function of applied d.c. voltage, very similar to CV techniques used for characterization of MOS capacitors.

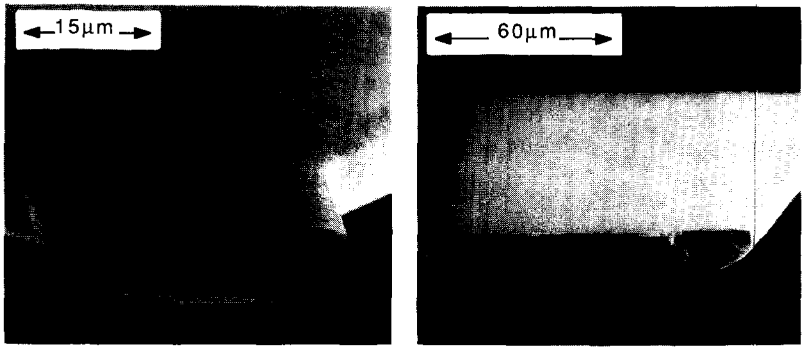
2. MEASUREMENT OF FRACTURE STRESS

In order to measure the fracture stress of boron-doped silicon structures, cantilever beams of varying widths and lengths were fabricated. Figure 1 shows the structure of one of these beams as well as a photomicrograph of fabricated beams showing side and cross-sectional views. In order to measure the fracture stress, the



STRUCTURE OF A HEAVILY BORON-DOPED SILICON BEAM

SIDE VIEW ALONG THE LENGTH OF A HEAVILY BORON-DOPED BEAM



CROSS-SECTIONAL VIEWS OF FRACTURED SILICON CANTILEVER BEAMS

Fig. 1. Structure of a heavily boron doped silicon cantilever beam and side and cross-sectional views of fabricated beams.

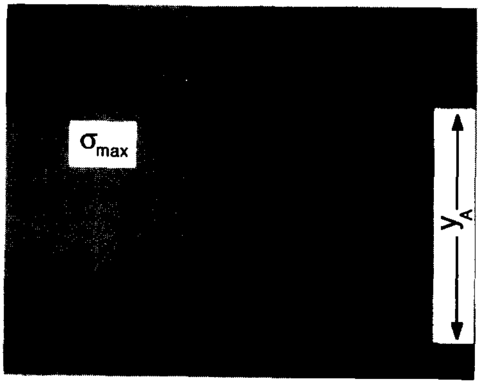


Fig. 2. A silicon beam under deflection. Measurement of the tip deflection is used to calculate the maximum stress at the bottom of beam where fracture occurs.

beam is subjected to a load applied laterally at the tip of the beam, as shown in Fig. 2. The maximum stress $\sigma_{\max}$ at the bottom of the beam as the tip is deflected is calculated to be[9]

$$\sigma_{\max} = \frac{3Ety_A}{2L^2} \tag{1}$$

where L is the shank length, t is the thickness, E is silicon's modulus of elasticity (Young's modulus), and y_A is the maximum deflection at the beam tip. Therefore, by bending the beams until fracture occurs and by measuring the top deflection y_A at fracture, one can calculate the fracture stress using eqn. (1). As evident from eqn. (1), the maximum fracture stress is a function of probe thickness, length, and Young's modulus. In these measurements it is assumed that the Young's modulus for silicon is 1.9×10^{12} dyne cm^{-2}. The value of maximum deflection y_A is measured using a microscope and a micrometer grid. Figure 3 shows the measured fracture stress as a function of cross-sectional area for a number of different beams. All beams had a thickness of 15 µm with varying widths. A large number of silicon beams were subjected to this test and the scatter of the measured fracture stress is shown in the figure. It is shown that the fracture stress of silicon substrates with small cross-sectional area is a factor of five to six higher than that of bulk silicon. The largest fracture stress measured was 1.8×10^{10} dyne cm^{-2} which was obtained for the smallest beam. This is expected since in single-crystal, pure, brittle materials, fracture is typically initiated on the surface at some type of surface defect resulting in stress concentration. As the total surface area reduces, the probability of occurrence of a "critical" surface flaw decreases resulting in higher fracture stress limits. This also explains the apparent scatter in measured data points. These results clearly show that thin silicon substrates are quite flexible and do not break easily. These results have also been observed by other investigators who have measured much higher fracture stress values for small silicon structures[10].

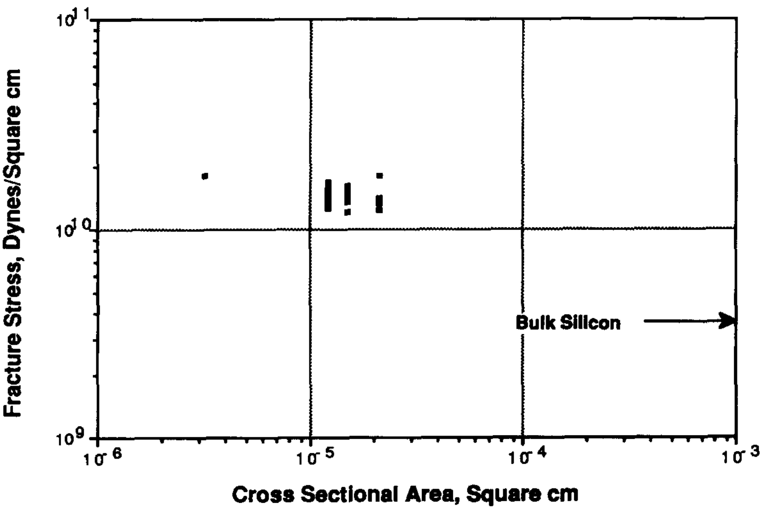


Fig. 3. Measured fracture stress as a function of cross-sectional area of boron-doped silicon beams. The scatter in measured values is also shown. All beams tested had a thickness of 15 µm.

3. MEASUREMENT OF YOUNG'S MODULUS AND INTRINSIC STRESS

In order to measure the Young's modulus and intrinsic stress of heavily boron-doped silicon structures, a new structure developed for measurement of these properties for a variety of thin films has been employed[11]. Figure 4 shows the test structure used for these measurements. It is a doubly supported bridge fixed at two ends with a capacitive drive electrode in the middle. The bridge is free standing and stretched due to its intrinsic tensile stress. The top capacitor plate is much thicker than the thin support beams that are anchored to the glass substrate by two support posts (glass and silicon are electrostatically bonded together over the area of the support posts). Figure 5 shows top and side views of fabricated bridge structures using heavily boron-doped silicon. The process uses a deep boron diffusion to form the support posts for the bridge and the thick center capacitor plate, and a shallow boron diffusion to form the beam[3]. For structures shown in Fig. 5 the beam thickness is 2.5 μm, the capacitive gap is 2.5 μm, and the width is 100 μm.

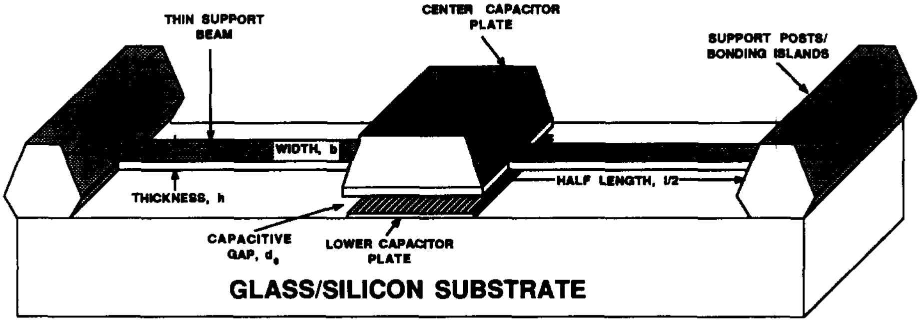


Fig. 4. The test structure used for the measurement of Young's modulus and intrinsic stress of heavily boron-doped silicon microstructures.

When an electrostatic voltage V is applied across the capacitor C, a normal force is exerted on the support beams, through the thick center plate, causing them to deflect. The electrostatic force is counterbalanced by the axial force P created by the intrinsic tensile stress. As the electrostatic voltage increases, the amount of beam deflection increases until the beam collapses since the force due to intrinsic stress cannot maintain equilibrium against the electrostatic force. This maximum value of the voltage is called the characteristic pull-in voltage V_{PI} and is given by [11,12]:

$$V_{\mathrm{PI}}^2 = \frac{8}{27} d_0^3 \frac{kP}{\varepsilon_0 A}\left[\frac{kl}{4} - \tanh\left(\frac{kl}{4}\right)\right]^{-1} \tag{2}$$

where A is the capacitor plate area, d_0 is the initial plate separation, $k = (P/EI)^{1/2}$, l is the total length of the beam, E is the Young's modulus, and I is the moment of inertia for the beam given by $I = bh^3/12$, b being the width and h the thickness. It is seen that eqn. (2) is a function of both E and P. If two test structures with the same beam dimensions except for having two different lengths are fabricated, their pull-in

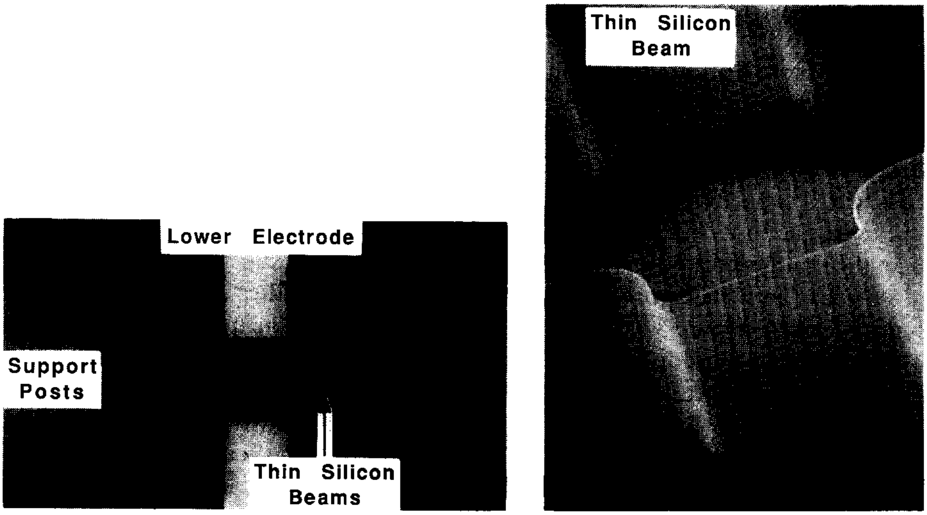


Fig. 5. Top and side views of bridge structures fabricated using heavily boron-doped silicon.

voltages will be different depending only on the beam length. It is thus possible to uniquely calculate E and P using the two values of the pull-in voltage obtained for these test structures using eqn. (2). The intrinsic stress σ can be calculated by dividing P by the cross-sectional area of the bridge which is equal to bh. The accuracy in the measurement of the Young's modulus and the intrinsic stress is determined by the accuracy with which the beam thickness, the capacitor plate separation, the pull-in voltage, the beam width, and the beam length can be measured. Based on eqn. (2) and the relationships for k and the moment of inertia I one can show that E and σ have the following proportionality relationships to beam dimensions and pull-in voltage:

$$E \propto \frac{l^2 V_{\mathrm{PI}}^2}{bh^3 d_0^3} \tag{3}$$

$$\sigma \propto \frac{l V_{\mathrm{PI}}^2}{bhd_0^3} \tag{4}$$

These relationships define the accuracy of the measurement of Young's modulus and intrinsic stress as a function of the beam dimensions and the pull-in voltage. The pull-in voltage of the bridge is typically between 50 and 100 V and can be measured with a maximum error of about 0.5%. The length of the bridge is typically 400–800 μm and it can be measured with a variety of techniques with an accuracy of better than 0.5%. The width of the beam is typically 50–100 μm and it too can be measured with better than 0.5% accuracy. The thickness of the bridge is 1–3 μm and it can be measured with an accuracy of about 1%, although it is possible to improve this to better than 0.5%. Finally, the capacitor plate separation is typically 2–3 μm and it too can be measured with a 1% accuracy by measuring the zero-force capacitance. Based on these and eqns. (3) and (4) the overall accuracy of the measurement is approximately 10%–15%. It should be noted that for large deflections of the beam, eqn. (2) will not be very accurate as the increased build up of tension in the beams alters the value of P. However, in the present situation the maximum deflection of the bridge before its collapse is typically 0.1–0.2 μm, and since the beam thickness is about 2.5 μm eqn. (2) still applies without introducing a large error.

Using the above technique, the Young's modulus and intrinsic tensile stress for (110)-oriented silicon were measured. The Young's modulus was measured to be $\approx (2.0\text{–}2.2) \times 10^{11}$ Pa which is about 20% higher than undoped silicon. The intrinsic tensile stress was measured to be $\approx 1.83 \times 10^{7}$ Pa which agrees well with the measured values obtained using pressure–deflection characteristics of thin diaphragms. Taking into account the errors in our measurements, we believe these values are accurate within 15%–20%. The increase in Young's modulus with increasing intrinsic stress has also been observed by others in LPCVD silicon nitride films.

These measured mechanical properties of boron-doped silicon thin films is sufficiently different from undoped silicon to warrant their use in simulating and analyzing the performance characteristics of silicon sensors and actuators. Indeed, the value of the intrinsic tensile stress of boron-doped silicon greatly affects the sensitivity of pressure and tactile sensors[1,3]. The measured force sensitivity of a 1024-element tactile imager and the calculated sensitivity using the above value for the intrinsic stress agree quite well.

4. CONCLUSION

Fracture stress, Young's modulus, and intrinsic tensile stress of boron-doped silicon microstructures with doping concentrations above 5×10^{19} cm^{-3} have been measured. The maximum fracture stress is measured to be 1.8×10^{10} dyne cm^{-2} which is a factor of five to six higher than bulk silicon (*i.e.* silicon structures with dimensions in the millimeter range). This agrees well with measured results from undoped silicon whiskers. Fracture is initiated on some kind of a surface defect and as the total surface area becomes smaller the fracture stress decreases. The Young's modulus is measured to be $\approx (2\text{–}2.2) \times 10^{12}$ dyne cm^{-2} and the intrinsic tensile stress is 1.83×10^{8} dyne cm^{-2}. These values are believed to be accurate within 15%–20%. These results should help improve the accuracy of simulated performance characteristics of silicon microsensors and microactuators that utilize boron-doped silicon films.

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