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Reshaping of Single-Crystal Silicon Microstructures

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This paper deals with the reshaping technology for realizing three-dimensional (3-D) microstructures through plastic deformation of single-crystal silicon (SCS) films by applying Joule heating. SCS beams are used for determining the behavior of SCS microstructures during reshaping. The reshaped SCS structure has a sharp corner at a point where stress and heat are concentrated. The plastic deformation caused by flow stress results in permanent 3-D shapes.

KEYWORDS: 3-D structures, reshaping technology, self-assembling, SDA, dislocation motion

1. Introduction

There are a number of technologies for fabricating three-dimensional (3-D) microstructures out of two-dimensional (2-D) silicon thin films.[1–3] Reshaping technology is one of the essential processes for realizing 3-D microstructures based on 2-D silicon films. A polysilicon structure fabricated by a surface micromachining process is permanently deformed into a 3-D shape using this technology.[4]

Single-crystal silicon (SCS) has a uniform crystal structure compared to polysilicon, so its mechanical properties are better than those of polysilicon. SCS is plastically deformed at temperatures higher than 650°C.[5–7] This implies that SCS can also be reshaped by Joule heating if the temperature can reach 650°C. In this respect, we examine the reshaping of SCS microbeams fabricated from silicon-on-insulator (SOI) wafers.

2. Principle

The basic concept of the reshaping process is illustrated in Fig. 1. A microstructure is fabricated on an SOI wafer [Fig. 1(a)], then raised by a manually controlled microprobe [Fig. 1(b)]. Joule heating is performed by passing a current through the structure. Joule heat generated in the buckled beam far from the substrate does not dissipate much, resulting in reshaping [Fig. 1(c)]. Finally, the structure has a fixed 3-D shape after releasing the external forces [Fig. 1(d)].

3. Fabrication Process

Several microstructures are fabricated from SOI wafers for the Joule heating experiments. Two SOI wafers with 1-μm-thick and 5-μm-thick top layers are used for the fabrication of the test structures. Figure 2 shows the fabrication process of the SCS microstructures for the reshaping experiment. Phosphorus-doped-silicate-spin-on-glass (PSG: OCD type P59230) is spun on the SOI wafer [Fig. 2(a)]. Diffusion of phosphorous was conducted at 1000°C for 1 h to obtain the resistivity of around 10^{-4}–10^{-5} Ωm. After the removal of PSG, the top layer is patterned and etched by reactive ion etching (RIE) [Fig. 2(b)]. The photoresist-assisted release[8] is performed, whereby the patterned photoresist layer acts as a mechanical reinforcement for supporting the microstructures during the wet etching and drying processes [Fig. 2(c)]. The photoresist pattern is subsequently removed with O_2 plasma for the dry release of the structures [Fig. 2(d)].

4. Reshaping of SCS

4.1 Experimental results

The typical length and width of the test structures are 400 μm and 10 μm, respectively. Two groups of beams with 1 μm and 5 μm thickness are used. Typical resistance values are around 2 kΩ for 1 μm beams and 400 Ω for 5 μm beams. The amounts of current input for reshaping the 1-μm- and 5-μm-thick beams are 5–6 mA and 14–16 mA, respectively. Figure 3 shows the SEM micrograph of the reshaped SCS microstructures. After the current is applied for between 3 s and 120 min, the reshaped profiles are measured by using a focusing microscope.

The reshaped profiles of the 5-μm-thick SCS beams with an applied current of 14.5 mA are shown in Fig. 4. Applied voltage fluctuated rapidly around 6 V. No reshaping phenomenon is observed with a current lower than 14 mA, while the structures are broken with an applied current higher than 16 mA. The color of the reshaped part is dark brown during Joule heating, and the profile shows a sharp corner after reshaping. Figure 5 shows the reshaping profiles of 1-μm-thick SCS beams. In Fig. 5(a), the structure is reshaped with an applied current of 5.5 mA. Applied voltage also fluctuated around 10 V. The reshaped part glows during Joule heating, and the profile shows a sharp corner after reshaping. This is different from the rounded corners of polysilicon structures reshaped with short current durations (2–15 s).[4,9] The color of the reshaped part of polysilicon beams is amber or orange, and the temperature is between 650–750°C during the reshaping.[9] This means the temperature of the glowing part of the 1-μm-thick SCS structure is higher than the temperature of the reshaped part of the polysilicon structure. Once the top corner is plastically deformed, no further plastic deformation occurs at other parts, since a large amount of stress is released at the corner. Figure 5(b) shows the rounded profiles of the 1-μm-thick SCS beams with lower current value and longer duration. This phenomenon can be explained by a surface effect. The effect of dislocation on the plastic deformation of a thin film is larger than that of a thick one, since the surface finish of the thin film is worse than that of the thick one relative to thickness. Dislocations grow in the film if stress is induced by increasing the duration of Joule heating, causing partial plastic deformation that results in rounded corners.

4.2 Analysis

The initial curvature of the structure before reshaping is measured in order to determine the maximum stress at the reshaped corner, for a given bending moment. The maximum

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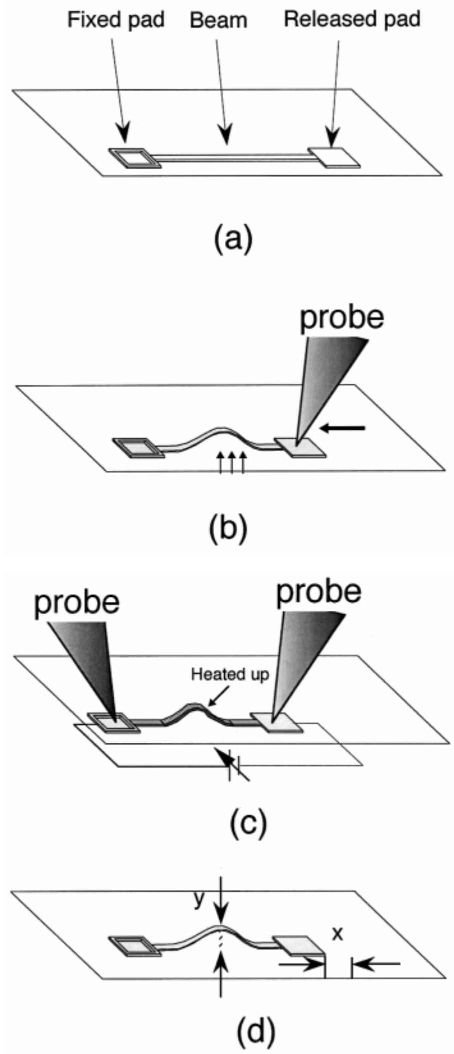

Fig. 1. Reshaping procedure. (a) Sample used for the experiments (b) Elastic deformation (c) Applying the current (d) Measurement of the reshaped profiles.

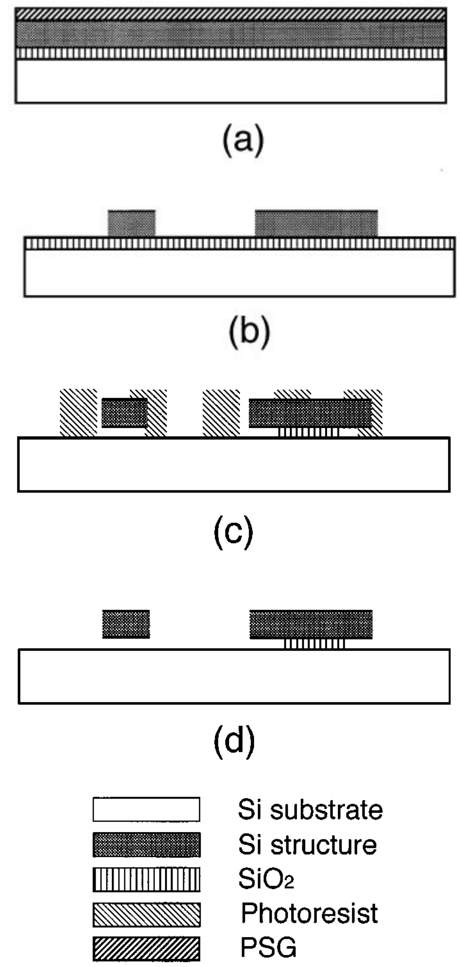

Fig. 2. The fabrication process for the test structures. (a) N-diffusion (b) Patterning (c) PR-assisted release (d) Removal of the photoresist.

stress, σ before reshaping is obtained by

$$\sigma = \frac{d}{2R}E \quad (1)$$

where E is Young's modulus, d is the thickness of the structure, and R is the radius of curvature of the top corner before reshaping. E is set to 190 GPa.[10] The calculated maximum stress of the 5-μm-thick structure in Fig. 4 is 12 GPa and that of the 1-μm-thick one in Fig. 5 is 2 GPa. The determination error due to the inaccuracy in measuring R is $\pm$15%.

The reshaping mechanism is explained using the stress-strain curve under high temperature, given in Fig. 6, based on the report of Pearson *et al.*[5] In our experiment, we changed the amount and duration of the applied current so that the temperature at the top corner varies, whereas the bending moment is fixed. If the maximum stress is lower than the yield stress at a certain temperature, the stress-strain behavior follows the elastic line. It jumps to the plastic line, however, once the stress exceeds the yield point at the given temperature. The SCS can either flow or fracture at the critical temperature between 600–650°C.[5] Thus, the temperature of the reshaped part of the SCS structure must be higher than or equal to the critical temperature.

The electric power consumed in the 5-μm-thick beam at 15.5 mA was approximately 1.8 times as much as that in the 1-μm beam at 5.5 mA. It is possible to assume that beams were in thermal equilibrium because the heating duration was much longer than the typical time constant of microbeams($\sim$0.1 s). The heat dissipation from the surface is nearly the same for the two beams; the heat conduction along the beam is larger for the thicker beam and caused the difference in electric power consumption. Direct temperature measurement during reshaping was attempted but failed because of highly nonuniform temperature distribution and the motion of deforming beams.

The calculated maximum stress of the 5-μm-thick structure is much higher than the yield stress of the SCS at point 'a' in Fig. 6, leading to plastic flow in the structure. The temperature of the reshaped part of the 1-μm-thick structure is expected to be much higher than the temperature where the 5-μm-thick structure is reshaped, since the reshaped part of the 1-μm-thick structure is much brighter than that of the 5-μm-thick structure. Thus, the calculated maximum stress of the 1-μm-thick structure is sufficient for the plastic flow. In the case of the structures in Fig. 5(b), the temperature might be lower than that at which the SCS can easily flow. The structure is slowly deformed with growing cracks or dislocations due to the surface effect.

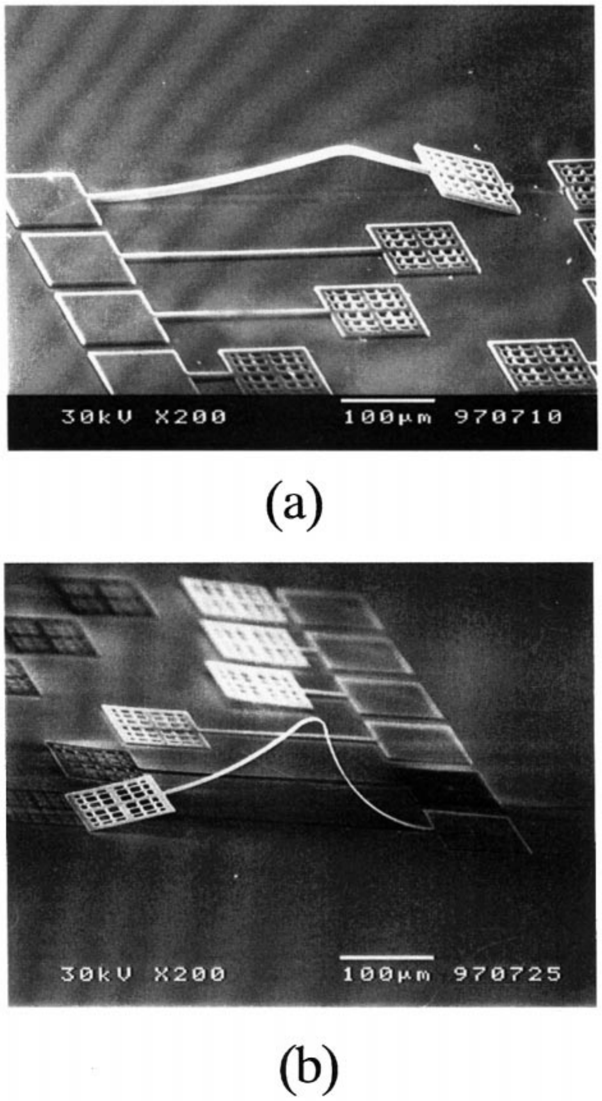

Fig. 3. SEM micrographs of the reshaped structures. (a) 5-μm-thick structure reshaped with a current of 15 mA. (b) 1-μm-thick structure reshaped with a current of 6 mA.

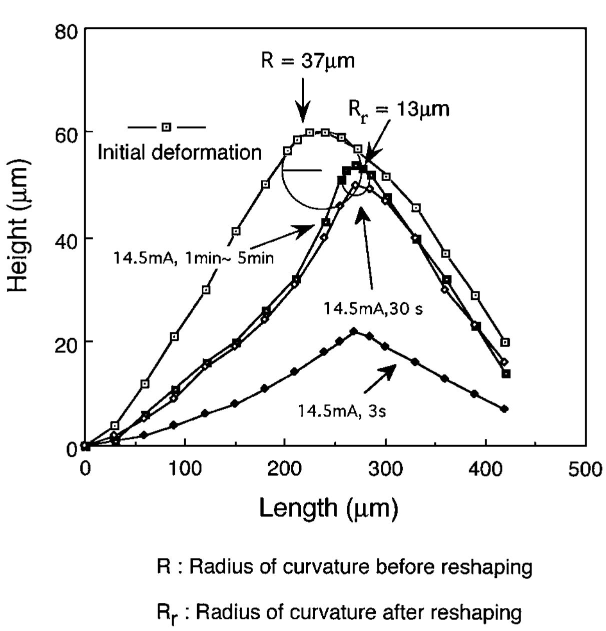

Fig. 4. The reshaped profiles of the 5-μm-thick structures.

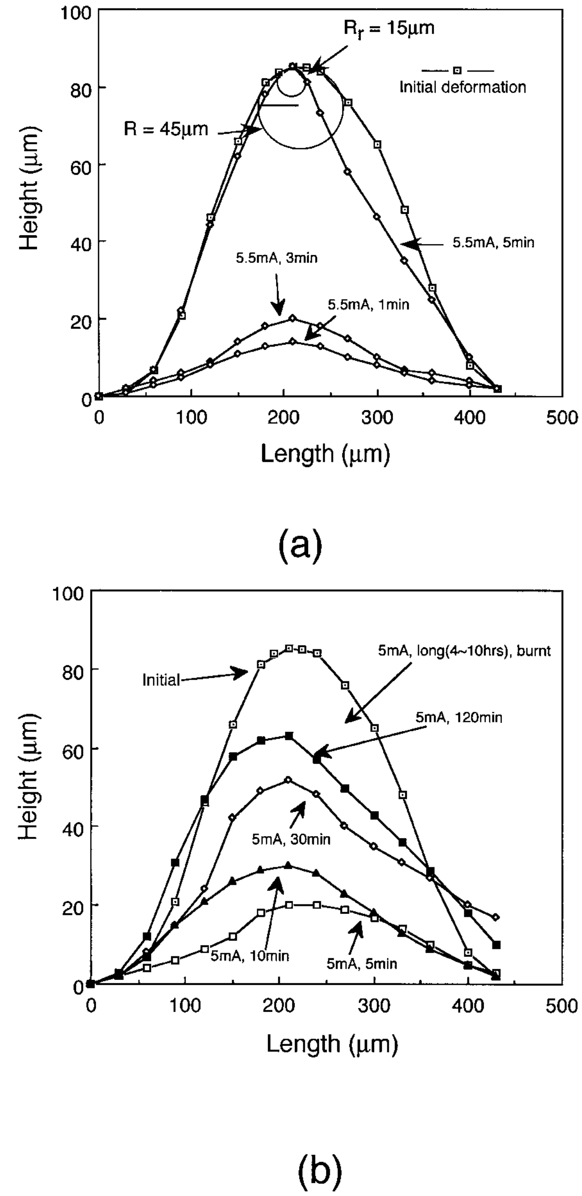

Fig. 5. The reshaped profiles of the 1- μm-thick structures. (a) with 5.5 mA (b) with 5 mA.

5. Discussions

5.1 Stress reduction during reshaping

The maximum stress σ_r at the top corner during reshaping (or at the final stage of the plastic deformation) is given as

$$\sigma_r = \frac{dE_r}{2R_r}\alpha \qquad (2)$$

where R_r is the radius of curvature of the top corner of the structure after reshaping, and E_r is the equivalent Young's modulus in the plastic range (see Fig. 6). α is a correction factor, since the curve of stress vs distance from the neutral axis becomes S-shaped, with the maximum slope at the center, when plastic deformation occurs. In this case, α is set to 0.67.[5] R_r also represents the radius of curvature during reshaping, since it remains the same once the structure plastically deforms. The calculated maximum stress of the 5-μm-thick structure during reshaping is 4.5 ± 0.7 GPa, assuming that the temperature is 700 ± 50°C. The determination error due to the measurement error of R_r is $\pm 20\%$. The

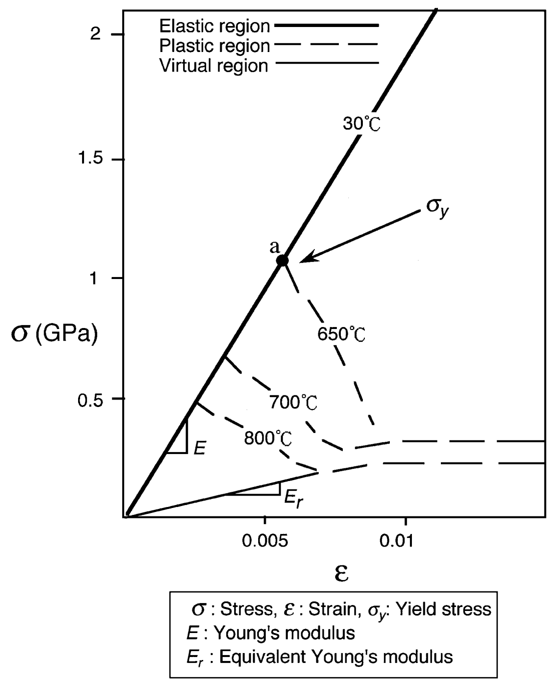

Fig. 6. Stress-strain behavior of SCS under high temperature.

calculated maximum stress for the 1-μm-thick film during reshaping is 0.6 ± 0.2 GPa, assuming that the temperature is 850 ± 200°C. The determined maximum stresses during reshaping are about one-third those before reshaping.

5.2 Difference between polysilicon and SCS

The polysilicon structure is reshaped with a rounded corner where the duration of current is short, while the SCS structure needs higher current values for reshaping and the structure has a sharp corner. We explain the different behaviors between SCS and polysilicon as follows.

In silicon where the chemical bonding is covalent, the directional nature of the bonds makes dislocation motion difficult. However, some dislocation motion does occur, especially at temperatures above about half the melting point, where the temperature is measured in Kelvin.[11] Since the temperature required for reshaping SCS is higher than or equal to the temperature at half the melting point of SCS, dislocation motion can easily occur, which contributes to the plastic deformation.

When Joule heat is generated in the beam, dislocations are generated due to the stress that exceeds the yield stress at elevated temperatures. There is a point where stress and heat are concentrated, so that the generation of dislocations starts at that point and traps dislocations moving along the beam. With SCS, there is no specific barrier to the dislocation motion, so that dislocations are free to move. The stress is easily released at the point where stress and heat are concentrated. This accumulation of dislocations causes the sharp coner in the reshaped SCS structure. On the other hand, polysilicon consists of many grains, each of which acts as a barrier to dislocation motion. Plastic deformation occurs locally in each part, since dislocations in a grain do not easily transfer to other grains. The stress is not completely released at one point, but is partially released in each part. This promotes the reshaping of the polysilicon structure throughpout the entire beam length, resulting in a rounded corner.

6. Conclusions

The reshaping technology of the SCS microstructures has been investigated. Flow stress plays the main role in the reshaping behavior. When plastic deformation begins, for a given bending moment, the maximum stress is less than it would be under room temperature, since both the radius of curvature and the stiffness decrease during reshaping. The reshaped SCS beams show sharp profiles, while the polysilicon beams show rounded profiles. This difference is caused by the different behavior of dislocation motion.

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1) K. S. J. Pister, M. W. Judy, S. R. Burgett and R. S. Fearing: Sens. & Actuat. A **33** (1992) 77.
2) M. Farooqui and A. G. R. Evans: Proc. IEEE Micro Electro Mechanical Systems Workshop, Nara, 1991, p. 69.
3) P. W. Green, R. R. A. Syms and E. M. Yeatman: J. Microelectromech. Syst. **4** (1995) 170.
4) Y. Fukuta, D. Collard, T. Akiyama, E. H. Yang and H. Fujita: Proc. IEEE Micro Electro Mechanical Systems Workshop, Nagoya 1997, p. 477.
5) G. L. Pearson, W. T. Read Jr. and W. L. Feldman: Acta Metall. **5** (1957) 181.
6) J. R. Patel and A. R. Chaudhuri: J. Appl. Phys. **34** (1963) 2788.
7) W. Schroter, H. G. Brion and H. Siethoff: J. Appl. Phys. **54** (1983) 1816.
8) D. Kobayashi, C. Kim and H. Fujita: Jpn. J. Appl. Phys. **32** (1993) L1642.
9) Y. Fukuta, T. Akiyama and H. Fujita: Trans. IEE Jpn. **117-E** (1997) 20.
10) K. E. Petersen: Proc. IEEE **70** (1982) 420.
11) N. E. Dowling: *Mechanical Behavior of Materials* (Prentice Hall, New Jersey, 1993) Chap. 2, p. 44.