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Determination of the modification of Young's modulus due to Joule heating of polysilicon microstructures using U-shaped beams

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Abstract

The modification of Young's modulus is determined before and after Joule heating generated by a current passing through polysilicon microstructures. U-shaped overhanging polysilicon beams are specially designed and fabricated to avoid both the heat transfer to substrate and the deformation by thermal expansion. Joule heating is performed by applying a current of 10–20 mA for 5–10 s, making beams heat up. The measured resonant frequencies shift up or down after Joule heating, attributed to the stress relaxation or the oxidation of beams. The modification of Young's modulus is negligible, implying that material properties after the reshaping are not changed much.

Keywords: Reshaping technology; Young's modulus modification; Joule heating; U-shaped beam; Polysilicon microstructure

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1. Introduction

Polysilicon is a convenient material for MEMS technology, compatible with the surface micromachining process. It has a thermal deformation capability from which 3D microstructures can be realized. Plastic deformation of polysilicon under high temperature has already been observed [1,2]. Recently, microactuated construction of thermally deformed 3D polysilicon structures has been realized without external manipulation [3]. This technique involves reshaping technology [4], which is achieved by the Joule heating process allowing permanent 3D microstructures out of surface micromachined polysilicon films. A typical structure made by the reshaping technology is shown in Fig. 1 [3]. This plastic deformation by Joule heating gives a new capability for the construction of 3D surface micromachined polysilicon structures.

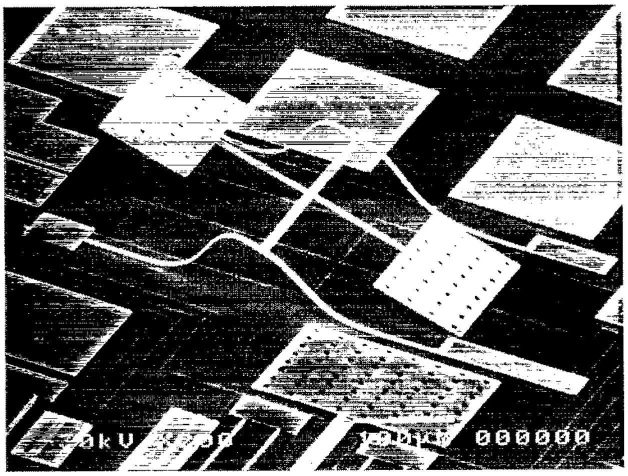

Fig. 1. The typical reshaped polysilicon structure.

Since the reshaping is completed within a few seconds at several mA, the annealing effect of the reshaping is different from that of a normal annealing process. As an important step of the study on this technique, we determine the Young's modulus modification after Joule heating generated by the current passing through polysilicon U-shaped beams. A resonance method [5] is used for determining Young's modulus. U-shaped overhanging polysilicon beams are specially designed and fabricated to protect them both from the heat transfer to substrate and from the deformation by thermal expansion. Several U-shaped beams with different dimensions have been designed and fabricated. The resonant frequencies and the beam deflections before and after the Joule heating have been measured.

2. Determination of Young's modulus

2.1. Principle

There are thresholds of the electrical input value and duration at which the reshaping phenomenon starts. It was

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observed that the reshaping of a beam (400 μm × 10 μm × 0.75 μm) needed a current value of several mA (voltage was 10–20 V) for several 10 s (the consumed energy was about 1 J) [4]. The beams were more easily reshaped at high current with short duration than at low current with long duration. The Joule heat generated in the flat beam attached to the substrate dissipated through silicon substrate, while the reshaped part of the buckled one was far away from the substrate, making it thermally insulated from substrate.

In this experiment, the silicon substrate under the U-shaped beam is etched away to avoid the heat sink effect by the substrate during Joule heating. The U-shaped beam is designed to minimize the deformation by thermal expansion during Joule heating. The concept of the U-shaped beam is illustrated in Fig. 2.

In order to find the relationship between Young's modulus and resonant frequencies of U-shaped beams with various lengths, finite element simulations (ANSYS™) have been performed for the beams with different dimensions. Modal analyses are used for determining the first mode natural frequencies of U-shaped beams. For the modeling of the structure, the following hypotheses have been taken into consideration: (1) The U-shaped beam is considered as a conservative oscillator. No damping phenomena are included in the simulations. (2) The free end plate of the beam is supposed undeformed, while the other ends of the beam are completely fixed. Fig. 3 gives simulation results on l^{-2} vs. the resonant frequency of beams (25 μm in width and 1 μm in thickness) with different Young's modulus, where l is the length of the U-shaped beam. The resonant frequency of the U-shaped beam is proportional to l^{-2}, which is the same as the case of the resonant frequency of a free undamped beam directly proportional to l^{-2}. Then, assuming the dimensional change of the beam is negligible, the relationship between the relative modification of Young's modulus, $\Delta E/E$ and the relative shift of the resonant frequency, $\Delta f/f$, is defined as [5]

$$\frac{\Delta E}{E}=2\frac{\Delta f}{f} \tag{1}$$

where E, f, ΔE and Δf are Young's modulus, the resonant frequency, the shift of Young' modulus and the shift of the resonant frequency, respectively.

2.2. Fabrication process

The fabrication process of the U-shaped beam structure is schematically illustrated in Fig. 4. A polyimide layer is used as a mechanical reinforcement during KOH etching and the subsequent wet etching process [6]. A 0.1 μm thick LPCVD Si_3N_4 layer and a 1 μm thick LPCVD SiO_2 layer are sequentially deposited on n-type, 3 in., (100) oriented silicon wafers. The Si_3N_4 layer is used for both the etch mask and the etch stop, while the SiO_2 layer is for protecting the Si_3N_4 layer from the RIE process. Then, a 1 μm thick LPCVD polysilicon layer is deposited and subsequently doped from

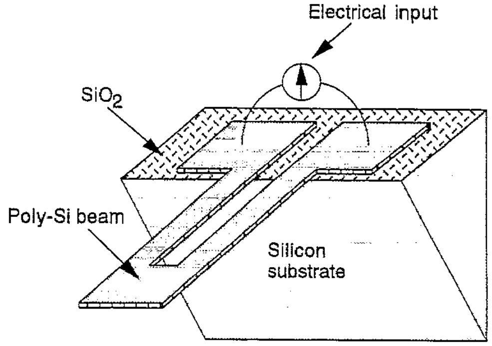


Fig. 2. A schematic view of the U-shaped beam.

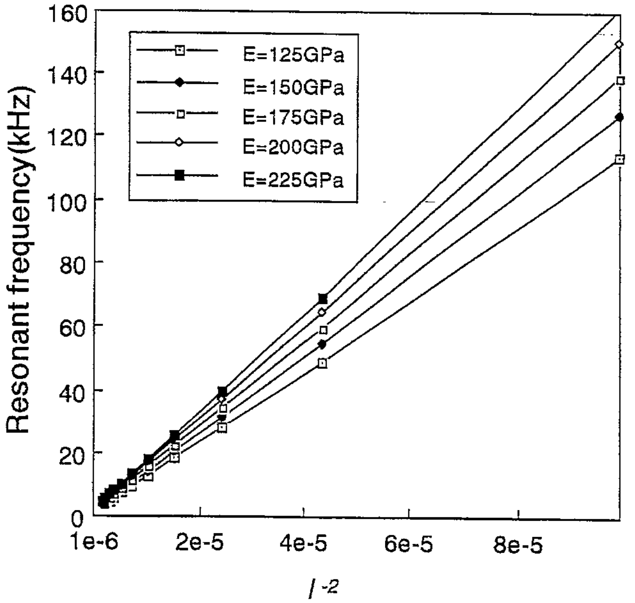


Fig. 3. The simulation results (for beams 25 μm in width and 1 μm in thickness).

P-Si-SOG (OCD type P59230). After annealing the wafer at 1100°C for 1 h, polysilicon layers on both sides of the wafer are patterned and etched by RIE with SF_6 gas. The backside window is patterned and etched by RIE with SF_6 gas. A 5 μm thick polyimide (PIX-L110SX) layer is spin-coated, baked at 120°C for 1 h and subsequently annealed at 350°C for 2 h. The backside window is etched in the KOH (33%) solution at 77°C for 3 h. During the KOH etching, the frontside of the wafer is covered by a Teflon cap to prevent the polyimide and polysilicon layers from being etched away in KOH solution. After etching the exposed Si_3N_4 etch stop layer by RIE with SF_6 gas, the remained SiO_2 layer in the backside window is removed in the BHF (buffered HF) solution. The polyimide covering the frontside of the beams is removed by O_2 ashing (RIE with an O_2 gas) for 30 min. As the final process, the temporary supporting beams are removed by YAG laser illumination. Fig. 5 shows a SEM photograph of the fabricated U-shaped beams.

2.3. Measurement and determination

The block diagram of the measurement system is shown in Fig. 6. The resonant frequencies of the fabricated U-shaped

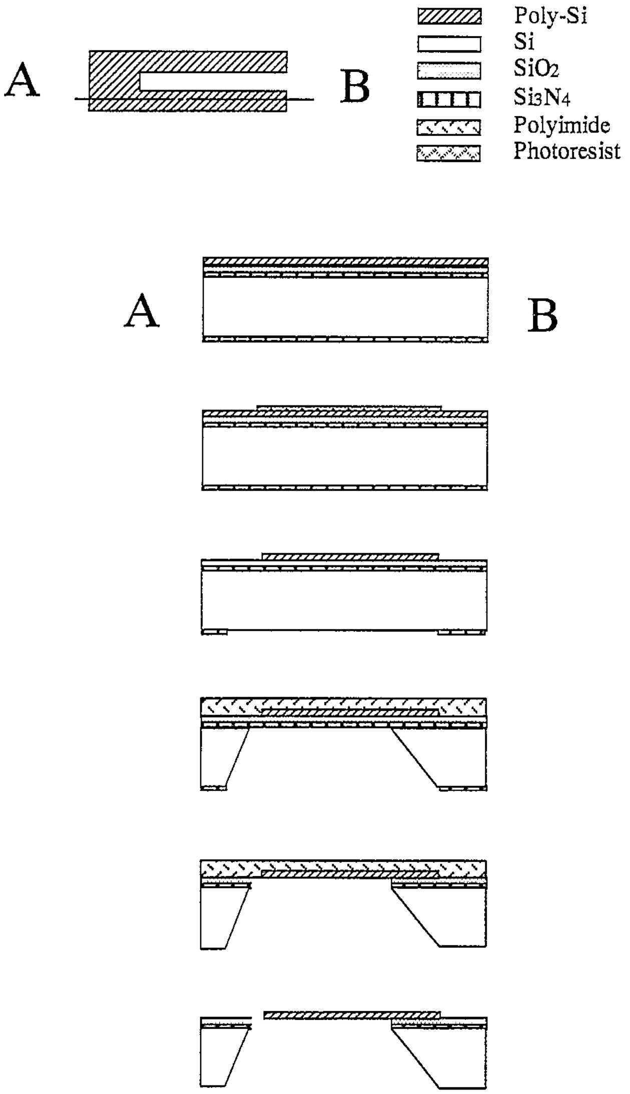


Fig. 4. The fabrication process of polysilicon beam structures.

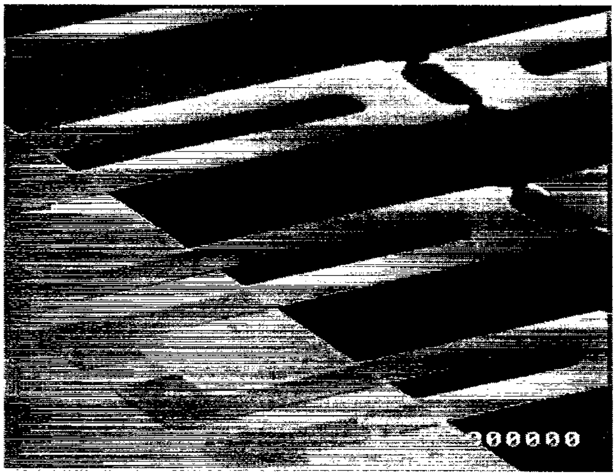


Fig. 5. The SEM photograph of the fabricated U-shaped beams.

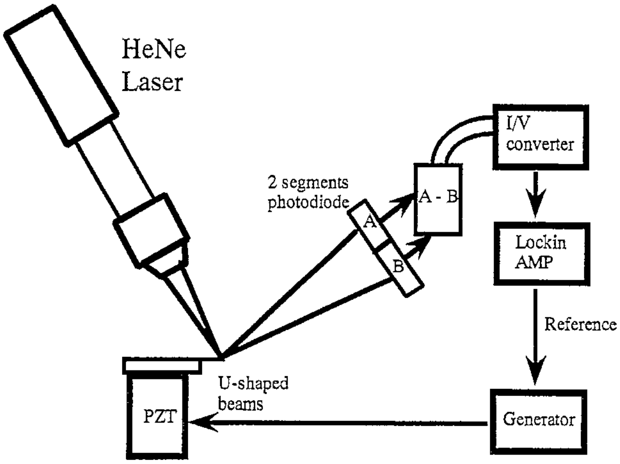


Fig. 6. The schematic representation of the measurement system.

polysilicon beams are measured by exciting them using a PZT actuator, detecting the resonant mode using a laser beam, which is received by a photo-sensitive diode (PSD) connected to the computer through signal conditioning circuits. The measured and the calculated resonant frequencies vs. l^{-2} are depicted in Fig. 7. The measured data deviate from the straight line, due to the deflection by the residual stress gradient of the fabricated beams. U-shaped beams with different dimensions are heated up with the Joule heat generated by the current passing through the beams. Since this input value depends on the dimension of the beam, the electrical input is regulated by observing the color of the beam during Joule heating. When the reshaping is in process, the color of the reshaped part of the beam is amber or orange. Fig. 8 shows the photographs of the U-shaped beams during the Joule heating process (applied current of 20 mA). After the Joule heating process, the resonant frequencies of the beams are again measured.

Two types of U-shaped beams are tested. The beams of Type A are 2 μm in thickness and those of Type B are 1 μm

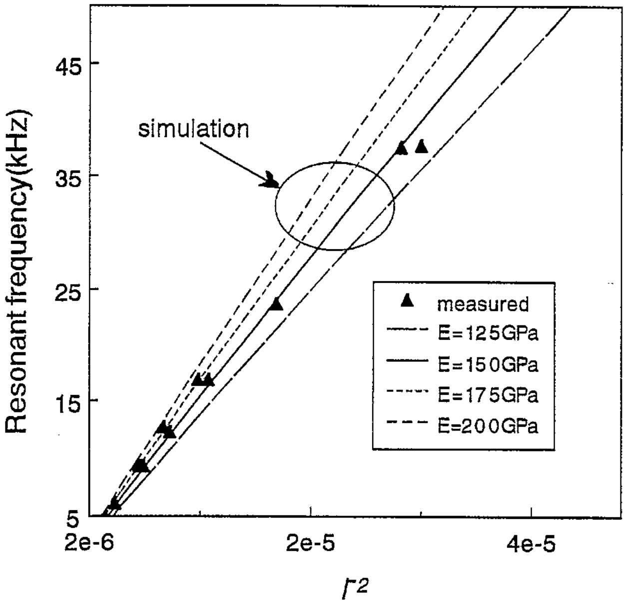


Fig. 7. The measured and calculated resonant frequencies vs. l^{-2}.

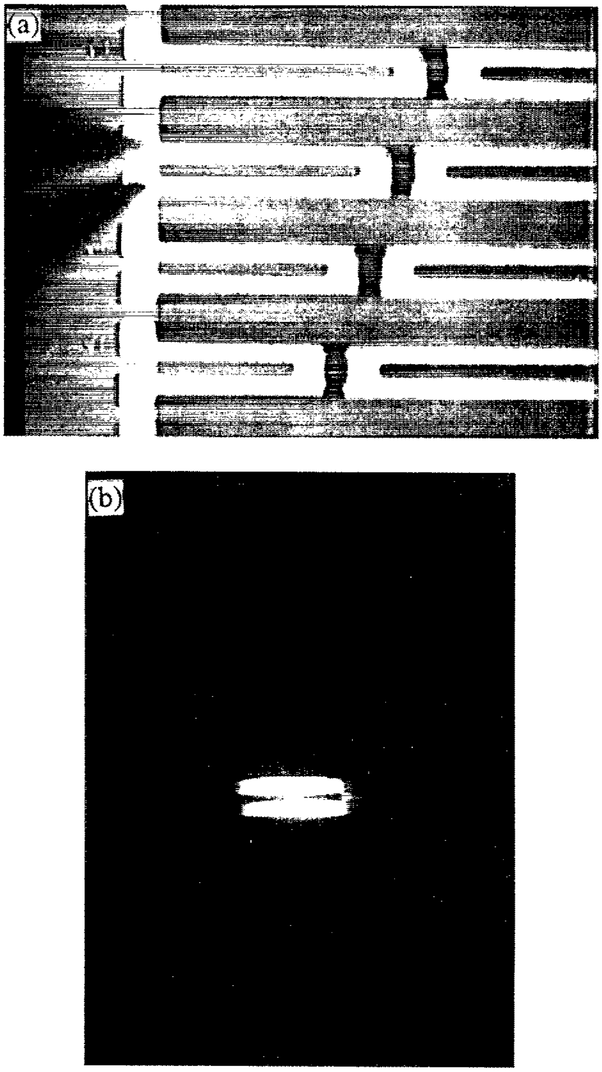


Fig. 8. The photographs of U-shaped beams during Joule heating process.

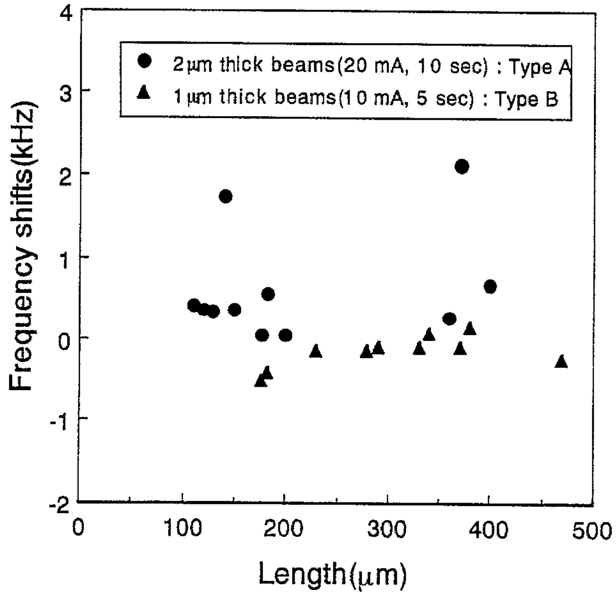


Fig. 9. The measured resonant frequency shifts after Joule heating.

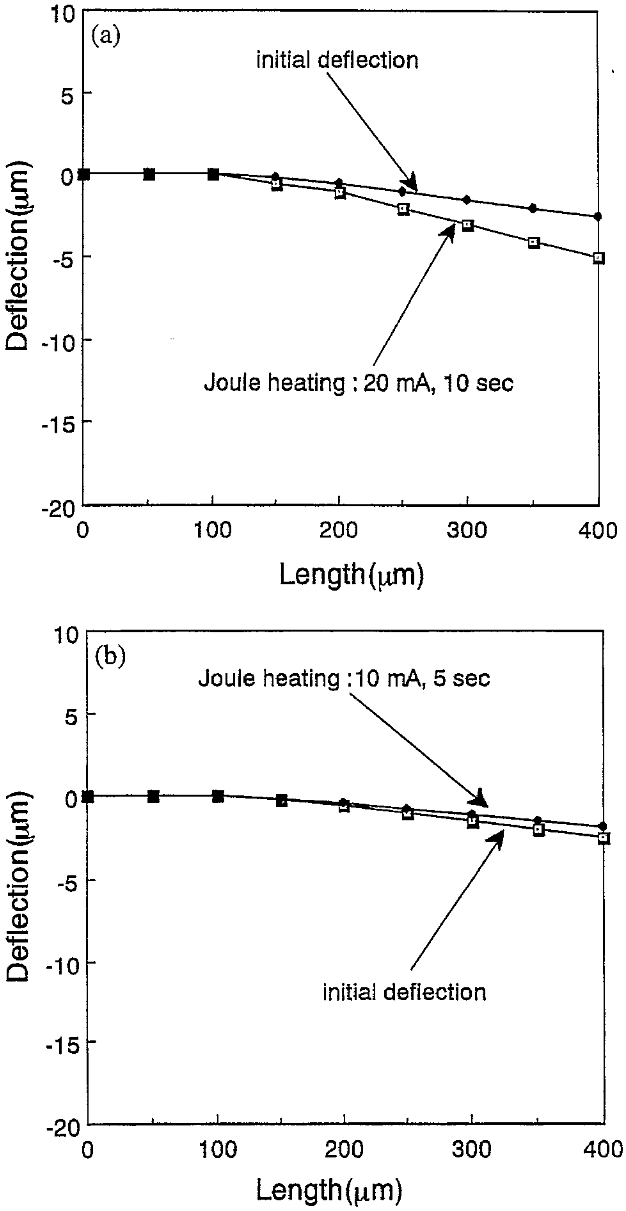


Fig. 10. The typical deflection profiles of the beams of Type B after Joule heating: (a) Joule heating with 20 mA; (b) Joule heating with 10 mA.

in thickness. Fig. 9 shows the shifts of the measured resonant frequencies after Joule heating. The resonant frequencies shift up or down in a range of 1 kHz. The resonant frequencies of most beams of Type A increase after Joule heating, while those of Type B decrease. In order to explain this phenomenon, we have measured the deflection of beams before and after Joule heating. The beams are initially curled down (about 0.5% of length) due to the internal stress gradient. The beams of Type A are curled down after Joule heating (20 mA, 10 s), while those of Type B are straightened after Joule heating (10 mA, 5 s) as shown in Fig. 10. The relative modification rates of Young's modulus are determined using Eq. (1), as shown in Fig. 11. The modification rates are determined to be less than ±3%.

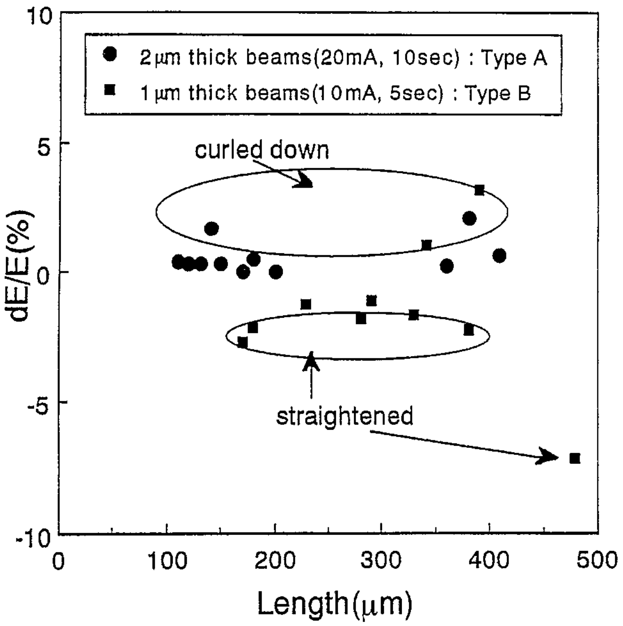


Fig. 11. The determined relative modification of Young's modulus.

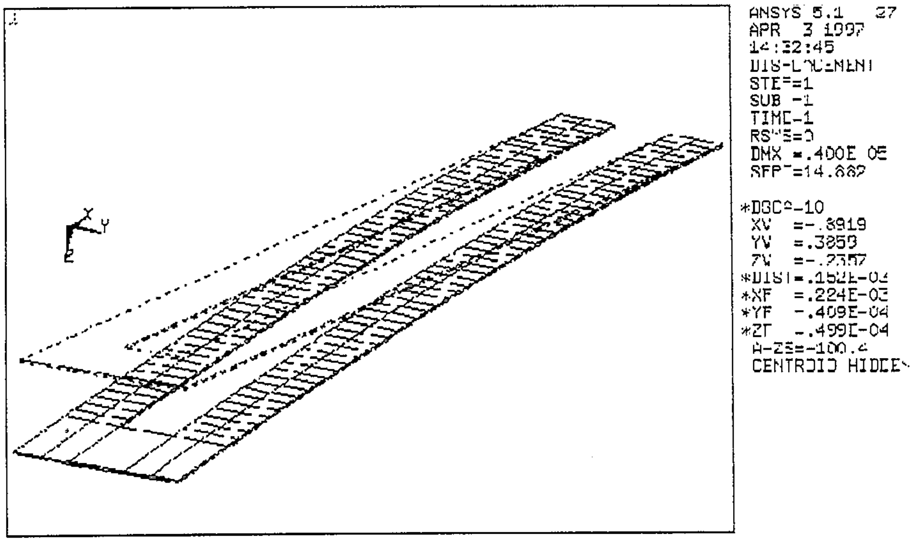
3. Discussion

In order to explain the effect of the deflection due to Joule heating on the resonance frequency of U-shaped beams, several finite element simulations (ANSYS®) have been performed. A standard thickness of 1 µm has been chosen and Young's modulus is set to 120 GPa. Two different types of simulations have been made. First, flat U-shaped beams are deformed by applying forces parallel to the front surface of the beam in order to reproduce an internal stress gradient, resulting in the beam curling down that is similar to the case of the fabricated beam deformed by the residual stress gradient as given in Fig. 12. Second, a U-shaped beam curled without stress is considered to check the variation of the resonant frequency by deformation of the beam. The simulation results are shown in Fig. 13. Resonant frequencies of U-shaped beams curled without internal stress are slightly lower than those of flat ones. However, the frequency variation due to the deflection is not so high even for a large beam deflection (50% of the length). On the other hand, resonant frequencies of beams curled by the internal stress gradient which produces an equivalent beam deflection of around 1% of the length are much higher than those of flat ones without internal stress. This means that the effect of the internal stress gradient on the variation of the resonant frequency is much stronger than that of the deformation.

The deflection of beams is affected by the amount of the electrical input. The beams are straightened by Joule heating with a proper electrical input range (10 mA) at which the reshaping occurred. In this case, it is reasonable to assume that the residual stress gradient is somewhat released by the annealing effect of Joule heating, making beams straighten and resonant frequencies decrease. This assumption is compatible with the simulation results of Fig. 13. On the other hand, the beams of Type A are curled down by Joule heating with higher current input, during which the color of the heated part during Joule heating is almost bright yellow. This means the temperature should be higher than 900°C [4,7]. At this temperature, the beams are oxidized, causing the resonant frequencies to increase. When the reshaping of a polysilicon beam is in progress, the temperature of the reshaped point is around 650°C [4], at which the oxidation may not occur in a few seconds. In this respect, the determined modification depicted in Fig. 12 is attributed to the stress relaxation and the oxidation during Joule heating.

4. Conclusions

The determination of the modification of Young's modulus of polysilicon beams due to Joule heating has been demonstrated by measuring resonant frequencies before and after



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*YF  -.409E-04
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Fig. 12. The finite element modeling (ANSYS®) of the curled structures.

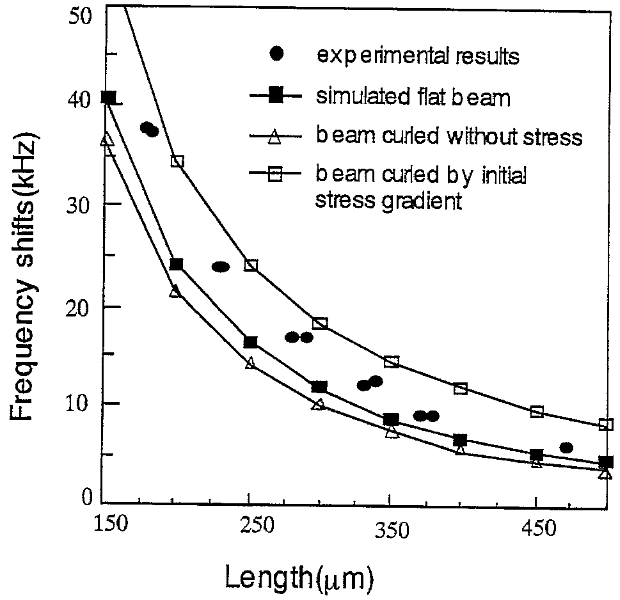

Fig. 13. The simulation results of resonant frequencies of curled U-shaped beams.

Joule heating of specially designed U-shaped beams. The stress relaxation and the oxidation during Joule heating affect the resonant frequencies of U-shaped beams, giving errors in determining the modification of Young's modulus of the beams. Considering this effect, we conclude that Young's modulus is not changed much after Joule heating. This means that the same material properties can be used as parameters in the simulation for the estimation of the behavior of reshaped 3D microstructures. This determination technique will provide a new analysis parameter to perform the modeling of the reshaping process with Joule heating, realizing the construction of desired 3D microstructures.

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Biographies

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Hiroyuki Fujita received the BS, MS, and PhD degrees in electrical engineering from the University of Tokyo, Japan, in 1975, 1977, and 1980, respectively. In 1980, he joined the Institute of Industrial Science at the University of Tokyo as an Associate Professor, where he investigated acoustic emission phenomena from fatigue cracking of metals and electrical discharges in solid insulators. From July 1983 to June 1985, he was with the Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology (MIT), Cambridge, MA, as a Visiting Scientist, where his research activities were acoustic emission monitoring of superconducting magnets and cryomechanics, the study of the mechanical properties of materials at cryogenic temperature. He is currently a Professor at the Institute of Industrial Science at the University of Tokyo. His current research interests include micromachining technology, microactuators, and micromechatronics. Dr. Fujita is a member of the IEEE, the Japanese Society of Cryogenic Engineering and the Japanese Institute of Electrical Engineering. He is an Associate Editor of the Journal of Microelectromechanical Systems.