The Reshaping Technology for Three Dimensional Polysilicon Microstructures

Member	Yamato FUKUTA	The University of Tokyo
Non-Member	Terunobu AKIYAMA*	The University of Tokyo
Member	Hiroyuki FUJITA	The University of Tokyo

Summary

This paper presents a new reshaping technology which is suitable to realize real three dimensional silicon microstructures. In this process, the elastically deformed polysilicon structure is annealed by Joule heating generated by the current passing through the structure. Plastic deformation occurs resulting in permanent three dimensional shapes. The application of this basic process to different polysilicon structures is successfully performed. Some quantitative characteristics of the annealing effects are also investigated by means of structure deformation measurements.

Key words: *micromachining, poly-silicon, plastic deformation, 3-D microstructure*

1. Introduction

The ability to realize three dimensional (3D) structures is a key step for micromachine technology. Several excellent processes for 3D structures have been already proposed such as the hinge based structures [1] for integrated optics [2] or the LIGA process [3].

On the other hand, polysilicon is a very convenient material for MEMS because of its compatibility to the CMOS process. One interesting property of polysilicon is thermal deformation capability. A hemispherical dome was fabricated by expanding polysilicon membrane with pressure at elevated temperatures [4] and thin polysilicon suspension can be even cut by local heating [5].

In order to fulfill the needs for 3D processes, we have proposed a new technology to fabricate 3D polysilicon structures, named "reshaping technology". In this technology thermal plastic deformation is used. A structure fabricated by the surface micromachining technology can be deformed to an arbitrary 3D shape with this technology.

Figure 1 schematically illustrates the process. Micro structures fabricated by the surface micromachining technology are first elastically deformed or lifted up with manually controlled micro probes. Next, electric power is supplied through the probes, and due to the an-

Figure 1 The schematic illustration of reshaping technology.

nealing effect of the Joule heat, the plastic deformation of polysilicon occurs resulting in permanent 3D shapes.

We have several motivations to develop the technology.

- Since surface micromachining technology is well investigated, it is advantageous to extend it to 3D structures by just adding post processing.
- It will be possible to integrate electric circuit with microstructures, because polysilicon structure process is compatible with IC process. One example is an array of cold cathode emitters fabricated above

*present address: Institute of Microtechnology, University of Neuchâtel, Switzerland

Figure 2 Fabrication process of the structure used for a reshaping technology

thin film transistors [6].

- Refilling [7] of the trench in a substrate and releasing the structure can make a structure thicker than deposited thin film structure.
- Compared with mechanical connection, motion within an elastic deformation range is smooth and flexible.
- Full electrical control of the fabrication process of 3D structures will be realized by integrating microactuators to deform the microstructure [8] instead of manual operation.

2. Fabrication and the reshaping process

(2.1) Fabrication The fabrication process of the structure used for the reshaping technology is schematically illustrated in Fig.2. First, trenches of high aspect ratio are made in the silicon substrate by anisotropic reactive ion etching in which CF_2Cl_2 and SF_6 plasma is used with Cr mask (step 1 and 2). (Nevertheless, these trenches are not essential for the reshaping technology and the substrate can be also directly oxi-

Figure 3 SEM image of reshaped beams with end plates.

dized.) These trenches are $10\mu\text{m}$ deep and lengths and widths are in the $2\sim 20\mu\text{m}$ range. Step 3, the surface of the substrate and trenches are thermally oxidized in wet ambient to obtain $0.4\sim 1\mu\text{m}$ thick oxide. Then, the surface is covered and the trenches are filled with LPCVD polysilicon on the oxide (step 4). At that stage the polysilicon is doped from poly-boron film (PBF) and subsequently annealed. (A sheet resistance of $40\ \Omega/\square$ is obtained.) The reshaping technology is applied to this polysilicon layer. Step 5, the polysilicon structures are patterned by anisotropic reactive ion etching using SiCl_4 and SF_6 plasma with photoresist as mask. In order to avoid sticking onto the silicon substrate during the polysilicon releasing, the PR assist method [9] is used. In this method, the patterns are first covered by a fine-mesh pattern of photoresist. Then, the wafer is dipped in HF for 20 minutes, and the released polysilicon structures which have anchors to the substrate are obtained (see step 7 in Fig.2). Finally, the resist pattern is totally removed by O_2 plasma.

(2.2) The reshaping process As displayed in step 7 in Fig.2, the polysilicon structure consists of an arm and two pads; one pad is fixed on the substrate and the other one is free. In the first stage, the unfixed pad is lifted up with a micro-probe to give an elastic deformation to the arm. In the second stage, voltage is applied between the fixed and the lifted pads as shown in step 8 in Fig.2. Subsequently, since Joule heat raises the temperature high enough to cause annealing effect, the stress in the arm is released and plastic deformation occurs. After removing the voltage, the arm cools down, and the structure keeps its 3D shape.

(2.3) Examples We constructed the 3D structures shown in Figs.3 and 4. Figure3 shows permanently deformed polysilicon beams with end plates. These beams are $2\mu\text{m}$ in thickness, $10\mu\text{m}$ in width and the

Figure 4 SEM image of an end plate framed with trench.

Figure 5 Fabrication process of the structure used for a reshaping technology

lengths are 400, 300, 200 μm , respectively, from left to right on the SEM picture. The reshaping current was set to 3.5 mA with 2~3second duration. (For the longest beam, the corresponding applied voltage was 15 V.)

In the Fig. 4, the end plate is framed with thick polysilicon obtained from the trench-filling, and the arm has a spring shape. The plate size is 100 μm ×100 μm and thickness is 2 μm . After reshaping, this structure could be vertically actuated by electrostatic force.

3. Investigation

This technology consists of two steps; initial elastic deformation and the Joule heating. Then, we have two parameters to control the technology; value of deformation and the electric energy of the Joule heating.

We can control the initial deformation by properly designing the shape of polysilicon structures. In this study, we used a simple shape (a beam) and examined the effect of electrical input to obtain final deformation which was different from the initial form.

So, we measured such subjects as follows.

- The electrical input versus reshaped results. This includes two measurements; the input current value or input time versus reshaped results, the V-I characteristics during the Joule heating.
- The surface temperature during the Joule heating.

(3.1) Profile measurements The detailed influence of the applied electric power on the reshaping process is investigated. The initial polysilicon structure is a one-end-fixed beam depicted in Fig. 5. As shown in Fig. 5(b), the unfixed pad is slid over a distance of 60 μm to obtain an elastic deformation of the beam. After applying electric power, the height of the beam, 'y', is measured as a function of the position, 'x', along the beam as shown in Fig. 5(c).

(1) The electric input versus reshaping profiles Figure 6 and Table 1 show the results with different current values applied during a given time (30sec.). Figure 6 illustrates the profiles of reshaped buckled beams. The applied current ranges from 0.0mA (no annealing) to 6.0mA. No permanent deformation was observed for currents lower than 2.0mA. At 3.0mA, the beam height is 15 μm at the highest point. The beam exhibits partial reshaping, but the profile is close to that of the flat beam. At 4.0mA, the beam height is 90 μm at the highest point. The profile is sharper than that of the 3.0mA, and closer to that of the initial shape. We can say that the reshaping effect of 4.0mA was much more pronounced than that of 3.0mA. In this case, the consumed electrical energy was 1.30J. The maximum deflection remains unchanged between 5.0 and 6.0mA. The corresponding profiles are almost the same. In such cases, we define that the beam is fully reshaped. We also define that the beam is partially reshaped if the beam deforms but is not fully reshaped.

Current(mA)	Time(sec.)	Energy(J)
2.00	30.0	0.277
3.00	30.0	0.902
4.00	30.0	1.30
5.00	30.0	1.54
6.00	30.0	1.92

Table 1 Electric input needed to the reshaping(current value is the parameter)

Figure 7 and Table 2 show the variation of the beam shapes for different annealing times at given current (4.0mA). Figure 7 schematically illustrates the profiles of reshaped beams with released pads. The reshaped profile after 10seconds exhibits partial plastic deformation.

Figure 6 Profiles of the structure at given time(30sec, current value is a parameter)

Figure 7 Profiles of the structure at given current value(4.0mA, flowing time is a parameter)

Current(mA)	Time(sec.)	Energy(J)
4.00	10.0	0.443
4.00	30.0	1.30
4.00	60.0 (1min.)	2.54
4.00	180.0 (3min.)	7.53
4.00	300.0 (5min.)	12.0
4.00	420.0 (7min.)	17.3
4.00	600.0 (10min.)	27.5

Table 2 Electric input needed for the rehaping(time is parameter)

tion. In this case, the consumed energy was 0.443J. We can say that at 4.0mA, the reshaping process can be

achieved very quickly.

Figure 8 shows the relation of the electric input versus the reshaped shapes of the buckled beams. With large current the reshaping can be realized in short time(about 10sec.), on the contrary, with small current the reshaping is incompleted even when the applying time is long(more than 10min.).

After reshaping, total length of the beam was $400\mu\text{m}$, which was the same value as the length of the initial samples. It means that the reshaping process makes no structure shrinking.

(2) Voltage versus Current characteristics Figure 9 shows the relationship between the applied current and the measured voltage for the flat and the elastically buckled beams. Note that the silicon substrate works as

Figure 8 Electric input versus reshaped shapes

Figure 9 Voltage drop as a function of supplying current (V-I characteristics)

a heat sink for the flat beam. Both currents are almost equal until 12V, but above this value, the current in the buckled beam exhibits higher value. At that time, the beam shines in orange due to Joule heating at the voltage higher than 10V.

(3.2) Temperature measurements

We measured the surface temperature of the structures in order to investigate the influence of the annealing effect and to explain the reshaping phenomenon.

Figure 10 shows the structure used for the temperature measurement. This was almost the same as that used for profiles measurement, but the width and the

Figure 10 Structure used for temperature measurements

thickness was different (the width was $20\mu\text{m}$ and the thickness was $0.60\mu\text{m}$).

We measured the temperature by using the surface temperature measurement system (Nippondenkisanei Thermomicro 6T04S). The measurement principle of the system is as follows; the infrared emission from a sample is detected by the high resolution infrared sensor (InSb based, with liquid nitrogen cooling). The infrared light is translated into electric signal and thus the surface temperature is calculated.

In this measurement, we employed conductive paste and wire bonding with metal electrodes (chromium and gold) instead of the probes.

Conductive paste was used to fix the structure in an elastically deformed shape and to render electric conductivity for Joule heating; we supplied current through the wires connected to the metal electrodes.

We had an error in the temperature measurement due to the defocusing problem of the microscope, since the height of the beam changed during the deformation. The error was estimated to be 10°C . Furthermore, we often observed the conductivity (or the current) fluctuating in a short time, because of the thermal breakdown of the current path; this was due to the current concentration, known as micro fuse phenomenon. In our case it was due to the ununiformity of the conductive paste. As a result, it was difficult to determine the temperature with high accuracy.

Table 3 shows one of the results. The sample used for this measurement was $400\mu\text{m}$ long, $20\mu\text{m}$ wide and $0.60\mu\text{m}$ thick, and doped with phosphorous. The reshaping current was increased from 0mA by 1.0mA. Supplying time of the current at each step was controlled manually, and was several seconds, long enough to measure temperature.

Current(mA)	Voltage(V) (Current supply)	Temperature(°C)	Brightness(color)
3.0	17	300	dark
4.0	21	460	bright (red)
5.0	24	540	bright (amber)
6.0	26	640	very bright (orange)
7.0	(unstabilize)	700-720	very bright (white)

Table 3 result of temperature measurement

4. Discussion

We suppose the reshaping process as follows: The Joule heat at the bending point causes the annealing effect of the material (polysilicon). Then, the initial stress due to the elastic deformation is released to reconstruct the structure, while the plastic deformation occurs. It is known that single crystallized silicon is plastically deformed at the temperature higher than 650°C [10]. Plastic deformation of polysilicon is observed [4].

From experiments in Section 3., it is suggested that there are thresholds of electrical input (flowing time or current value) at which the reshaping phenomenon starts. When the flowing time is 30sec., the threshold is 3~4mA, corresponding to about 1J of electric energy. When the current is 4.0mA, the threshold is shorter than 10sec., which corresponding to less than 0.44J of electric energy. From them, we may conclude that beams are more easily reshaped at large current value with short flowing time than at small current value with long flowing time.

From Fig. 9, we observed the difference of the conductivity between the flat sample and the buckled sample above 12V. The Joule heat generated in the flat sample dissipated through the silicon substrate. On the other hand, the buckled sample was far away from the substrate, therefore the Joule heat did not dissipate anywhere.

Moreover, in general, polysilicon has large conductivity at high temperature because of the property of polysilicon; conductive carriers are excited by thermal energy.

From those two reasons, we suppose that the temperature of the buckled beam was higher than that of the flat beam. Elastic deformation prior to current application is necessary to give an initial 3D shape but it also helps temperature rise which causes plastic deformation for reshaping.

The unstability of the V-I characteristic may come from the piezo-resistivity effect or the effect of the change of the polysilicon grains due to the internal stress

releasing, but this problem is under investigation.

5. Conclusions

We demonstrated the reshaping technology, a new method to have three dimensional microstructures from surface micromachined polysilicon films. We also performed experiments to investigate the technology. To understand basic reshaping phenomena, we used a simple structure, a buckled beam.

The relation between the electric input and the reshaped profiles was investigated. This investigation consists of two measurements. We measured the profiles of the reshaped beams at given current with supplying time as a parameter, or at given time with current value as a parameter. We measured voltage versus current characteristics.

The reshaping of a beam ($400\mu\text{m} \times 10\mu\text{m} \times 0.75\mu\text{m}$) needs the electric input of several mA (voltage is 10-20V) and several ten seconds (the consumed energy is about 1J). A beam is more easily deformed at large current values with short flowing time than at small current value with long flowing time. The reshaping phenomenon occurs at about 400-800°C, from the result of the temperature measurement.

Further study is under way in order to establish the technology to fabricate three dimensional microstructures having arbitrary shapes.

Acknowledgements The authors would like to thank Prof. Dominique Collard with LIMMS/CNRS in IIS, the University of Tokyo, for his valuable advice. The authors also would like to thank Fujita Laboratory staff for their helpful assistance.

(Received Aug. 8, '96; Revised Oct. 4, '96)

References

- (1) K.S.J.Pister, M.W.Judy, S.R.Burgett and R.S.Fearing, "Microfabricated Hinges", *Sensors & Actuators A*, 33, 1992, pp.77-82.
- (2) L.Y.Lin, S.S.Lee, M.C.Wu and K.S.J.Pister, "Micromachined Integrated Optics for Free-Space Interconnections", *Proceedings of IEEE Micro Electro Mechanical Systems Workshop (MEMS'95)*, Amsterdam, the Netherlands, January 29 - February 2, 1995, pp.77-82.
- (3) W.Menz, W.Bacher, M.Harmening and A.Michel, "The LIGA Technique-a Novel Concept for Microstructures and the Combination with Si-Technologies by Injection Molding", *Proceedings of IEEE Micro Electro Mechanical Systems Workshop (MEMS'91)*, Nara, Japan, January 30 - February 2, 1991, pp.69-73.
- (4) M.Farooqui and A.Evans, "Polysilicon Microstructures", *Proceedings of IEEE Micro Electro Mechanical Systems Workshop (MEMS'91)*, Nara, Japan, January 30 - February 2, 1991, pp.187-191.
- (5) G.Fedder and R.Howe, "Thermal Assembly of Polysilicon Microstructures", *Proceedings of IEEE Micro Electro Mechanical Systems Workshop (MEMS'91)*, Nara, Japan, January 30 - February 2, 1991, pp.63-68.
- (6) G.Hashiguchi and H.Fujita, "Monolithic Fabrication of Polycrystalline Silicon Field Emitters and Thin Film Transistors", *Technical Digest of the 13th Sensor Symposium*, IEEJ, Tokyo, June 8 - 9, 1995, pp.21 - 24.
- (7) C.Keller and R.Howe, "Nickel-filled Hexsil Thermally Actuated Tweezers", *Digest of technical papers of the 8th Int. Conf. on Solid-State Sensor and Actuators (TRANSDUCERS'95)*, Stockholm, Sweden, June 25 - 29, 1995, pp.376-379.
- (8) T.Akiyama and H.Fujita, "A Quantitative Analysis of Scratch Drive Actuator Using Buckling Motion", *Proceedings of IEEE Micro Electro Mechanical Systems Workshop (MEMS'95)*, Amsterdam, the Netherlands January 29 - February 2, 1995, pp.310-315
- (9) D.Kobayashi, C.Kim, and H.Fujita, "Photoresist-Assisted Release of Movable Microstructures", *Japan. J. Appl. Phys.* 32,2 (1993) pp.L1642-L1644.
- (10) G.L.Pearson, W.T.Read Jr., and W.L.Feldmann, "Deformation and Fracture of Small Silicon Crystals"; *Acta Met.*, vol.5 (1957), pp.181-191.

Yamato Fukuta received the B. S. degree in 1990 and the M. S. degree in 1996, in electrical engineering from the University of Tokyo, Tokyo, Japan. His research work is the investigation of three dimensional microstructures fab-

ricated by IC-compatible micromachining. He is currently with East Japan Railway Co.

Terunobu Akiyama was born in Tokyo, Japan, on October 10, 1966. He received the B. S., M. S. and Ph.D degrees in electrical and electronic engineering from Sophia University, Tokyo, Japan, in 1989, 1991 and 1994, respectively. He was a JSPS Postdoctoral Fellow in 1994 and 1995 and performed research on microelectromechanical systems in IIS of The University of Tokyo and in Institute of Microtechnology of University of Neuchatel, Switzerland, where he continues to work as Research Assistant. He is a member of the Japan Society of Applied Physics. He is interested in microelectromechanical systems employing Si planner processes.

Hiroyuki Fujita received the B. S. degree in 1975, the M. S. degree in 1977 and the Ph.D degree in 1980, all in electrical engineering, from the University of Tokyo, Tokyo, Japan. He is currently a Professor in the Institute of Industrial Science at the University of Tokyo, where he joined the faculty in 1980. His current research interests are system design and fabrication technologies of microelectromechanical systems. He also investigates autonomous distributed systems that mimic living organisms.