Realization and Characterization of Plastic Solar Cells

Vikas*, Prit Paul Singh**
*Lecturer, Central Institute of Plastics Engineering & Technology, Murthal Sonipat
** Manager (P/T) , Central Institute of Plastics Engineering & Technology, Murthal Sonipat
(Department of Chemical & Petrochemical, Ministry of Chemical & Fertilizers, Government of India)

Abstract

This paper describes Si plastic reshaping technique, Si origami, by combining focused ion beam (FIB) processing and wet etching. FIB is used as a nano tool for local etching as well as Ga ion implantation. The combination of Ga ion doping and alkali wet etching to a Si wafer enable us to fabricate a nanometer-thick Ga-ion-doped amorphous Si membrane, which can be bent to upward/downward at arbitrary angle by controlling FIB beam irradiation condition. The bending mechanism is discussed in the light of doped Ga ion distribution and collision cascade effect. The Si origami technique allows us to manufacture a micron-sized Si 3D structure like an airplane from a Si nano-membrane.

Key Words : Self-assembly, shape recognition, micro fabrication

I. Introduction

FIB is well known as a powerful tool for directly forming micro/nano-scale 3D mechanical structures without photolithography [1,2]. By using FIB with Ga ions, we can conduct Ga ion implantation as well as local etching. The combination of the ion doping and alkali wet etching to a Si wafer enables us to fabricate a nanometer-thick Ga ion doped amorphous Si membrane.

The nano-membrane will be utilizable as nano mechanical elements, such as nano force/pressure sensors and nano oscillators in nano-electro-mechanical systems. If the nano-membrane can be reshaped to arbitral 3D shape, the utility value will increase.

The purpose of this study is to develop Si nano-membrane reshaping technique using Ga ion implantation with FIB. The membrane is made by the combination of Ga ion implantation and wet etching [3-6], and it is bent to arbitrary angles by controlling the beam irradiation condition.

II. MEMBRANE FABRICATION

Fig. 1 illustrates process flow for fabricating and reshaping Si nano-membrane by using localized Ga ion implantation. First, Ga ion was irradiated with ion dose 7×1015 ions/cm2 in Si (100) surface to form a cantilever shape. The accelerating voltages were 40kV and 20kV, which ion penetration thicknesses can be estimated to be approximately 80 nm and 40 nm as shown in Figs. 2(a) and (b), respectively. The Ga ion distribution in Si was calculated using the stopping and range of ions in matter (SRIM), which is an ion impact analysis software program based on Monte Carlo simulation [7]. After the ion implantation, the samples were etched in 20□ TMAH solution at 90°C. Ga implanted portion remained after wet etching; thereby, the cantilever pattern was released from the substrate due to Si undercut. After that, by irradiating Ga ion beam to the fixed end only, the cantilever can be bent. The beam irradiation width was 500 nm.

Fig. 3 shows 3×5 self-standing cantilevers array. The

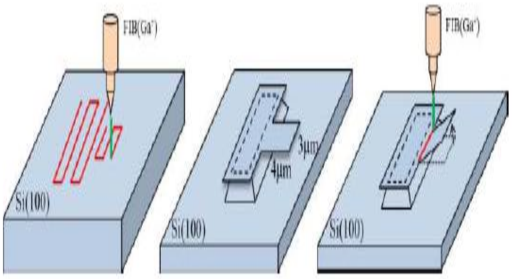
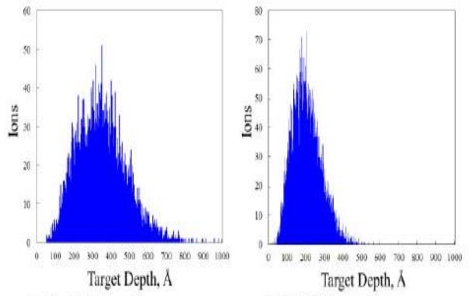


Figure 1: Schematic of fabrication process for Si Cantilevers using FIB ion implantation and wet etching.



(a) Ga+(40kV) into Si
(b) Ga+(20kV) into Si

Figure 2: Representative Ga ion implantation simulation results by SRIM

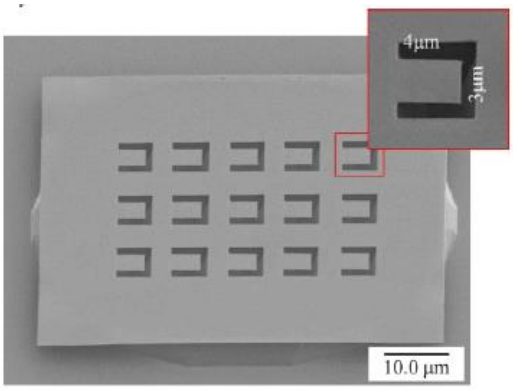


Figure 3: SEM image of Si Nano-cantilevers. Figure

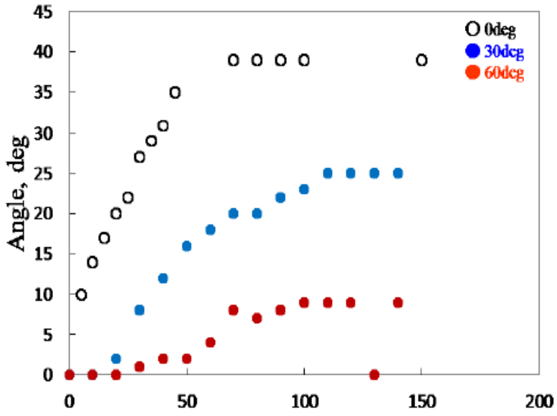


Figure 4: Relationship between the number of scan cycles

and cantilever's bent angle when the irradiation angles were 0~60°. thickness was estimated from side-view SEM images. The rectangle shape is finely formed in all the produced cantilevers, which indicates that FIB beam implantation is uniform. No bent and failed cantilevers were seen.

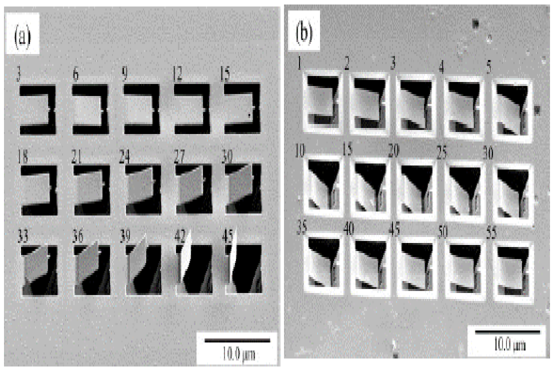


Figure 5: SEM photographs of bent cantilever beams at the accelerating voltages of (a) 40kV and (b) 20kV.

III. BENT BEAM FABRICATION

Fig. 4 shows the relationship between the number of scans and bent angle. The circle, triangle, and square plots indicate the FIB irradiation angles of 0, 30, and 60°, respectively. There angle values were defined as the angle between the FIB irradiation direction and the normal direction of cantilever surface. All the data were obtained at 10kV. In the irradiation angle of 0°, the bent angle linearly increases to 40° with increasing the number of scans to 50 cycles. Over 50 cycles, the bent angle was maintained at 40°. In the irradiation angle of 30°, the bent angle increases with almost half of the increasing rate in 0°.

The reached bent angle was 25°C. In the case of the irradiation angle of 60°, the bent angle increasing rate is very slow compared with the rates in 0 and 30°. As is well known, the difference in FIB irradiation angle to sample surface affects the penetration depth of Ga ions, which determines the bent angle of Si cantilevers. In this study, we decided to irradiate Ga ion beam at 0°perpendicular to the cantilever surface.

Figs. 5 (a) and (b) show representative reshaping results of Si nano-membrane cantilevers prepared by Ga ion doping with accelerating voltages of 40kV and 20kV, respectively. The number of the FIB scan cycles was changed from 1 to 55. All the cantilevers are found to be bent upward. The angle gradually increases with increasing the number of the FIB scan cycles. By contrast, the 20kV-formed cantilevers are bent downward, and the angle gradually increases with increasing the number of the FIB scan cycles. The bent direction and the angle are dependent on the relation between cantilever forming acceleration voltage and reshaping voltage.

Figs. 6 (a) and (b) show the relationship between the number of scan cycles and bent angle in the 40kV- and 20kV-formed cantilevers, respectively. The square, triangle, diamond, and circle plots indicate FIB implantation voltage of 2, 5, 10, and 40kV for bending, respectively. By the FIB local implantation at 2kV up to 70 cycles, the 40kV-formed cantilevers were not bent. Even in the number of scans greater than 70 cycles, the maximum bent angle was around 8°. At 5kV, the cantilevers were bent from 20 cycles. At 10kV, the cantilevers were rapidly bent up to 50 cycles, where the bent angle increasing rate was 0.77 deg/scan. In greater than 50 cycles, the angle was kept constant at about 40°. At 40kV, the bent angle increasing rate was approximately 2.0 times faster than 10kV. When the number of scans was 50, the bent angle reached 90°. All the 40kV-formed cantilevers were bent upward by the local FIB implantation from 2kV to 40kV.

In the 20kV-formed cantilevers, the relationship between scan number and bent angle at 2kV and 5kV FIB implantation shows a similar trend to that in the 40kV-formed cantilevers. However, at 10Kv implantation, the upward-bent angle reached 90° in irradiating FIB with 18 cycles. Moreover, when the FIB local implantation voltage was 40kV, twice of the voltage for cantilever forming, the cantilevers were bent downward, which is opposite direction to the 40kV-formed cantilevers. When the scan cycles were greater than 60, the cantilevers were bent upward. The bent angle and direction are found to be strongly associated with the balance of the cantilever forming voltage and the FIB local implantation voltage.

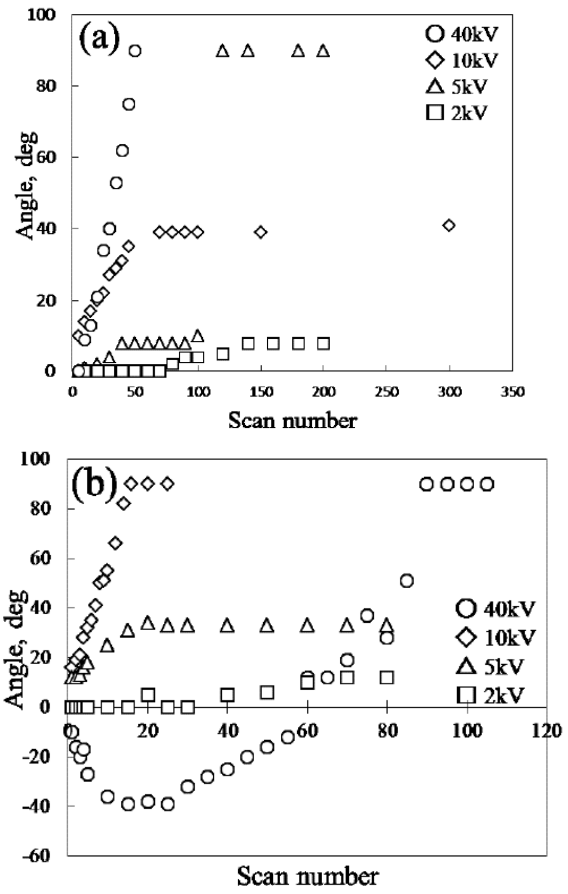


Figure 6: Relationship between the number of scan cycles and bent angle in the (a) 40kV and (b) 20kV-formed cantilevers. The square, triangle, diamond, and circle plots indicate FIB implantation voltages of 2, 5, 10 and 40kV for bending, respectively.

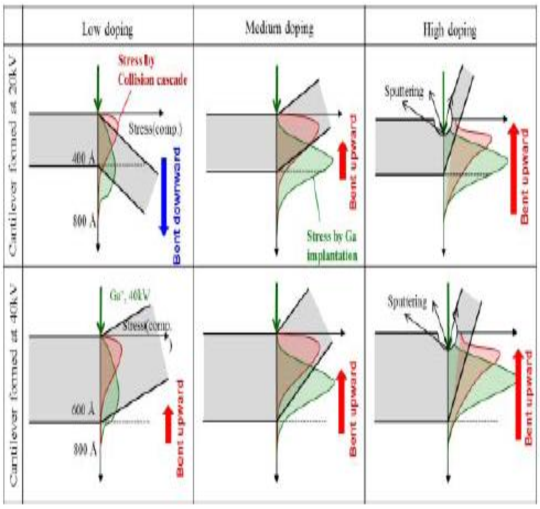


Figure 7: Schematic of the bent mechanism of Si Cantilevers using local Ga ion implantation.

Fig. 7 shows a schematic of the mechanism of Si cantilever bending by FIB local implantation. The bending of cantilevers is determined by penetration depth of Ga ion. When reshaping voltage is lower than cantilever forming voltage, the bent angle is determined by the ion doped portion in the thickness direction. As shown in Fig.3, the doped thickness depended on the accelerating voltage, and it was estimated to be around 80nm at 40kV. At 40kV, Ga ions are mainly distributed at around 35~50nm in depth from the surface. When reshaping voltage is higher than the forming voltage, some of the Ga ions are considered to go through the cantilever.

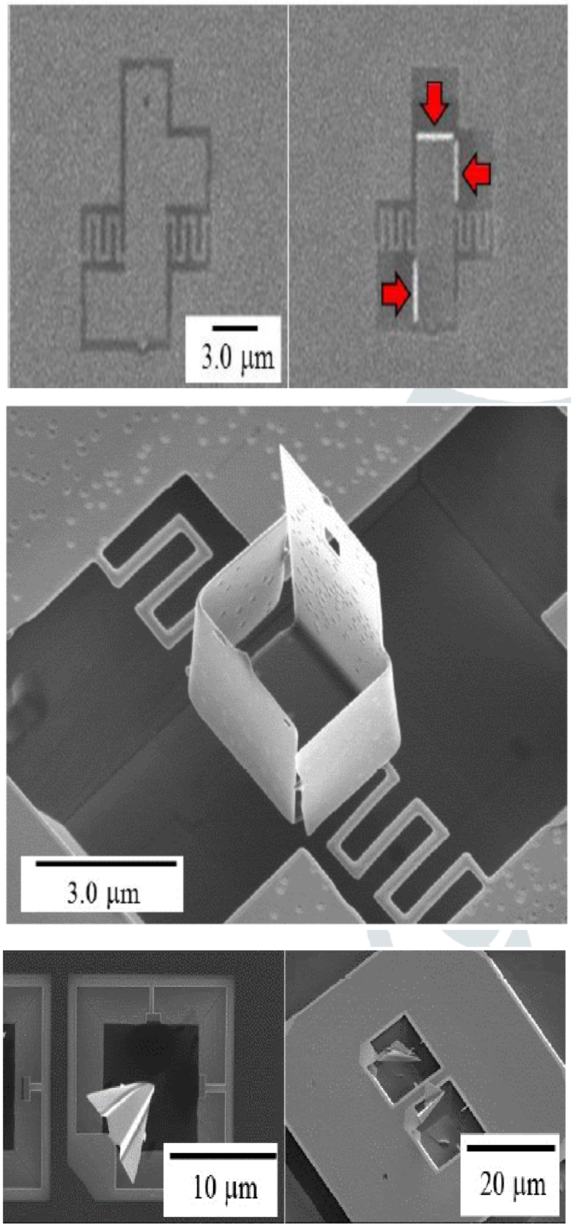


Figure 8: SEM photographs of submicron-sized paper airplane and box.

Owing to large influence of the collision cascade, therefore, the cantilevers are bent downward. When increasing the scan cycles, the scanned portion is thinned down, which would have yielded a large deformation of Si cantilevers.

IV. NANO MECHANICAL STRUCTURE

Based on the experiment results, we manufactured a micro-sized airplane and a box, as shown in Fig. 8. Like an actual "origami", Japanese traditional culture, we could fold a piece of Si nano-membrane into the figure of an airplane and a box at the micro scale. Si is well known to be brittle material, but we have demonstrated that plastic forming of Si is possible with FIB.

V. CONCLUSION

We proposed a new technique for manufacturing 3D structures using FIB. Si nano cantilevers were fabricated by means of Ga ion implantation and TMAH wet etching.

By irradiating Ga ion beam into the fixed end only, the cantilever could be bent in response to the irradiation condition. The bending mechanism was discussed in the light of doped Ga ion distribution and collision cascade effect. With the silicon origami technique, we successfully fabricated an airplane and a box made of Si. The technique proposed in this work would be applicable in fabricating more complex 3D structures.

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