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Surface damage in silicon co-implanted with He and H ions: Effect of H implant energy

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ABSTRACT

Cz n-type Si (100) wafers were singly or sequentially implanted with 160 keV He ions at a fluence of $5 \times 10^{16}/cm^2$ and H ions at a fluence of $1 \times 10^{16}/cm^2$ with different energies of 40, 110 and 160 keV, respectively. Surface damage, defect microstructures as well as H diffusion have been studied. Our results clearly show that depending on H energy, sequential implantation of He and H into Si could induce a series of surface features upon annealing. Localized surface exfoliation with thickness corresponding to H ion range is observed in He and 40 keV H ion co-implanted Si after annealing at temperatures of 600 °C and above, while large area exfoliation appears on the 110 keV H co-implanted Si surface at a depth close to the He ion range upon high temperature annealing. However, no clear surface damage is found on the post 160 keV H implanted and annealed Si. Results from transmission electron microscopy observations reveal that the post H ion implantation at different energies plays quite different role in thermal growth of He-induced micro-defects. The observed surface phenomena have been interpreted based on the defect creation, its evolution as well as H diffusion.

1. Introduction

The 'smart-cut' technology developed by Bruel [1] has been found to be an efficient way to produce high quality silicon-on-insulator (SOI) wafers. The technology is mainly based on the phenomenon that implantation of H ions at a sufficient fluence (a few 10^{16} cm^{-2}) could induce surface exfoliation of Si after subsequent annealing at several hundred degrees. This thin film separation process potentially allows SOI wafers to be produced more economically than the parallel processes such as separation by implantation of oxygen (SIMOX) and bond-and-etch-back silicon-on-insulator (BESOI) since the remained wafer can be re-polished and reused. Moreover, the 'smart-cut' technology has now attracted increasing interest of fabrication of several other combinations of semiconductors and insulators, building of multilayer substrates and devices, and matching of materials that can hardly be grown epitaxially [2–5].

Recently, in order to promote commercial application of such technique, more attention has been paid on decreasing cost of this technology. It has been demonstrated that H and He sequential implantation can significantly reduce both the total fluence and thermal budget necessary to achieve Si surface splitting [6,7]. However, since more gas ions have been involved, it makes difficult to clarify the interactions between two kinds of atoms and the defects induced by H/He atoms, and also the correlation between defects and H/He atoms. Although there has been a large amount of researches on the application and impact factors of the 'smart-cut' technology [8,9], the effects of involved ions and defects on bubble growth and surface exfoliation underlying this process are still not well understood, especially for H and He ion co-implanted Si.

In this work, high fluence 160 keV He ions were pre-implanted into crystalline Si samples to create a band of bubbles around He range. H ions were subsequently implanted into the same Si at different energies to introduce defects and H atoms at different depths. The effects of H ion energy on surface damage and defect microstructures have been presented and the underlying mechanism for surface damage have been discussed based on the interaction of defects and gas atoms induced by He and H ion implantation upon annealing.

2. Experimental details

Czochralksi (cz) n-type Si (100) wafers with a resistivity of 3–7 Ω cm were singly or sequentially implanted at room temperature with He and H ions. He ion implantation was performed with

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an energy of 160 keV and at a fluence of $5 \times 10^{16}/cm^2$, while H implantation was carried out at a fixed fluence of $1 \times 10^{16}/cm^2$, but with different energies of 40, 110 and 160 keV, respectively. SRIM (Stopping Range of Ions in Matter) 2008 code simulations reveal that the projected range (R_p) of He ions is about 1.0 μm, and those of H ions at energies of 40, 110 and 160 keV are about 0.5, 1.0 and 1.5 μm, respectively [10]. The implanted samples were subjected to furnace annealing in the temperature range of 400–800 °C with a flow of nitrogen gas for 1 h.

Scanning electron microscopy (SEM) was used to characterize surface morphology. The SEM observations were performed with a JSM-6700F field-emission electron microscopy operating at 10 kV. Atomic force microscopy (AFM) was carried out to quantitatively study three-dimensional surface topography and thickness of the exfoliated layer. Cross-sectional transmission electron microscopy (XTEM) was selectively used to investigate defect microstructures in some He and/or H implanted and annealed Si. Before XTEM observations, the samples were cut, glued, and then thinned using mechanical polishing and ion milling. XTEM images were taken at 200 kV with a JEOL 2010 microscopy. Moreover, H profiles in some of the implanted and annealed Si samples were also measured by elastic recoil detection analysis (ERDA), using a 3 MeV He^+ beam impinging the sample at 15° from the sample normal. The detector was placed at 30° from the sample surface. Additionally, slow positron annihilation spectroscopy (SPAS) was adopted to measure the vacancy-type defect profile. During the measurements, slow positrons were implanted with energies tunable between 100 eV and 25 keV. The Doppler broadening of the 511 keV annihilation γ rays was recorded at room temperature. The level of the Doppler broadening is indicated by the parameter *S*, which is defined as the ratio of the counts in a fixed central region ($|511 - E_\gamma| < 0.85$ keV) of the 511 keV line to the total counts of the peak ($|511 - E_\gamma| <$ 4.25 keV).

3. Results and discussion

According to SEM and/or AFM observations, no surface damage is clearly observed on Si samples singly implanted with He or H ions even after 800 °C annealing in the present study. However, significant surface modifications have been found on Si under sequential implantation of He and H ions upon annealing, which show strong dependence on energy of H ions. Firstly, for 40 keV H ion co-implanted Si, no surface damage has been clearly detected after annealing in temperature range up to 500 °C. However, as annealing temperature increases to 600 °C, localized exfoliation of Si surface occurs, which results in formation of numerous craters, as shown in Fig. 1(a). The craters have the size around 3 μm. Further increasing temperature up to 800 °C leads to less change in surface morphology, as shown in Fig. 1(b). Secondly, as for the 110 keV H ion co-implanted Si, craters resulting from the localized surface exfoliation appear at 500 °C. No significant changes in crater morphology and exfoliated area are clearly found in the annealing temperature range of 500–700 °C. As an example, Fig. 1(c) illustrates the SEM image showing craters formed on He and 110 keV H ion co-implanted Si after 600 °C annealing. One can see that the craters have average size around 10 μm, which is obviously larger than that found in 40 keV H co-implanted Si at the same annealing condition (Fig. 1(a)). Increase of the annealing temperature to 800 °C leads to large area surface exfoliation, leaving some irregular surface features like islands, as shown in Fig. 1(d). Thirdly, SEM observations only show flat and smooth surface for the 160 keV H ion co-implanted Si even after annealing up to 800 °C.

In order to acquire more information in the surface morphology, and also to quantitatively measure the exfoliated depth, AFM measurements have been performed for some of He and H co-implanted Si after 800 °C annealing. The results are presented in Fig. 2. From Fig. 2(a), one can see that besides the craters, lots of blisters could also be observed on the Si co-implanted with He and 40 keV H ions. The depth of crater is estimated to be about 470 nm, quite close to the R_p of 40 keV H ions (~0.5 μm), as shown in Fig. 2(b). Therefore, one can conclude that the localized exfoliation is achieved at the sample depth corresponding to 40 keV H implantation induced damage region. However, in case of the post 110 keV H ion implantation, only some island-like structures retain on Si surface upon 800 °C annealing owing to large area surface exfoliation (Fig. 2(c)). Through one of these surface structures, thickness of the exfoliated layer has been measured to be about 961 nm (Fig. 2(d)), which is well consistent with the R_p of 160 keV He or 110 keV H ions (~1.0 μm).

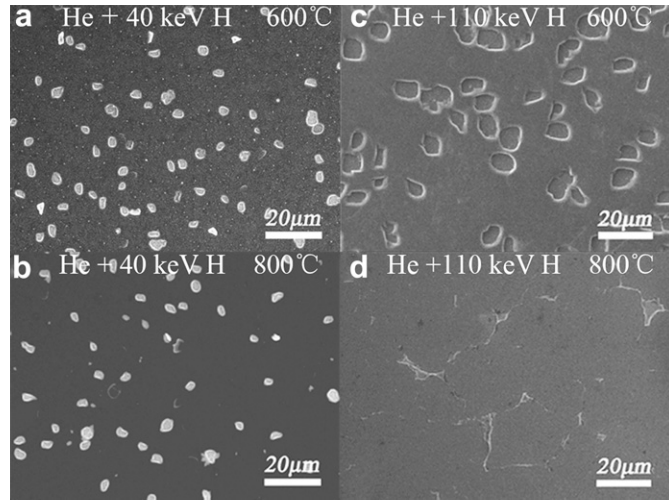

Fig. 1. SEM images of the Si samples sequentially implanted with 160 keV He and H ions at different energies followed by annealing at temperatures of 600 °C and 800 °C. (a) and (b) H implantation at 40 keV, (c) and (d) H implantation at 110 keV.

In order to explore the underlying mechanism for surface damage occurring on Si, XTEM investigations have been selectively performed for the implanted and annealed Si samples. A quite well-defined defect band is created around He ion range (~1.0 μm) in 160 keV He only implanted and 800 °C annealed Si, as shown in Fig. 3(a). The band is mainly made up of isolated cavities and a few of dislocations. The cavities have sizes ranging from 4.0 to 25.0 nm with a mean value of about 11.0 nm. However, XTEM observations only reveal dislocation loop-like defects in the 40 keV H only implanted and 800 °C annealed sample (Fig. 3(b)), which are mainly distributed at a depth close to the R_p of H ions (~0.5 μm).

Fig. 4 shows the XTEM micrographs of Si by successive implantation of 160 keV He and H ions at different energies and after 800 °C annealing. It is clear that two defect bands are created in the He and 40 keV H ion co-implanted Si (Fig. 4(a)). The shallower band is centered at a depth of about 0.5 μm from the surface, corresponding to defect region produced by 40 keV H ions. The band consists of a few large cavities (~90 nm) and fine cracks surrounded by large strain field. The deeper one is located around 1.0 μm from surface, corresponding to the defect region owing to He ion implantation. With close views of the band, one can find that it is mainly made up of cavities in large quantity as well as a few large dislocations (see the insert in Fig. 4(a)). The cavities in the band have an average size of about 6.0 nm, which is quite smaller than that found in the He only implanted and 800 °C annealed Si (~11.0 nm). Thus, the results clearly suggest that sequential implantation of He and 40 keV H ions in Si promotes the growth of cavities and strain field in the H-implanted region accompanied by