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Defect formation and thermal evolution in H and O co-implanted Si

Zhuo Wang [a,*], Jun Wang [b], Changlong Liu [b]

[a] School of Science, Tianjin University of Technology and Education, Tianjin 300222, China
[b] School of Science, Tianjin University, Tianjin 300072, China

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ABSTRACT

190 keV O and 40 keV H ions with different fluences were sequentially implanted into crystalline Si at room temperature. The surface damage and defect microstructures after subsequent annealing have been studied by optical microscopy (OM) and cross-sectional transmission electron microscopy (XTEM). The formation of surface damage depends strongly on both the H implant fluence and annealing temperature. After 400 °C annealing, surface blistering was first observed on Si co-implanted with O and H ions both at a relative high fluence, while no surface damage was observed on H-only implanted Si. Further annealing led to serious surface damage, such as blistering and localized exfoliation. According to statistics of the size of craters from exfoliated regions, O and H co-implantation could effectively increase the average size of the craters. XTEM observations have revealed that the additional high fluence O implantation could affect the thermal growth of H cavities. The surface damage and defect microstructures induced by O and H co-implantation were tentatively discussed considering the interactions between O, H implants and heavily damaged Si substrate.

1. Introduction

A sufficient fluence of H implantation into Si can cause a series of damage, such as cavities, platelets and even surface splitting [1–3]. Based on H implantation induced surface exfoliation and direct bonding methods, a novel technique named “Smart-cut” [4] has been developed to fabricate SOI structures economically and with better quality compared with prevalent SIMOX (separated by implantation oxygen) and BESOI (bonded and etch-back SOI) techniques. It is worth noting that lots of interesting materials could be exfoliated by H implantation and after subsequent annealing [5–7]. Therefore, the Smart-cut technology can be applied to produce many functional complex materials for the microelectronic industry.

In recent years, the effects of additional ion implantation on surface splitting induced by H implantation have received more and more attention. It was demonstrated that co-implantation of H with He, D or B ions has strongly influenced the surface damage processes compared to H-only case, leading to the reduction of the total fluence and thermal budget necessary for layer splitting [8–10]. Thus, it is interesting to study the internal interactions between H and other implants as well as the effects of co-implantation on surface damage. Generally, the layer splitting process by H implantation mainly proceeds through both chemical interaction (bond breaking, internal surface passivation) and physical interaction (gas coalescence, pressure and fracture) in the Si substrate [11]. Since O implantation could introduce gas atoms and create vacancy-like defects [12] along the ion range as H implants, co-implantation of O and H ions will bring benefits for surface damage. In this study, either H alone or O and H sequentially have been implanted in Si to nearly the same depth. The thermal evolution of surface damage has been observed and counted in detail. The possible mechanism for surface damage and the role of additional O implantation have been tentatively discussed in combination with XTEM observations.

2. Experimental

The (100)-oriented *n*-type crystalline Si wafers were sequentially implanted with 190 keV O and 40 keV H ions at room temperature. According to SRIM calculations [13], the projected ranges of O and H ions are nearly the same. The implantation experiments have been carried out twice for different research purposes. First we studied the effects of additional O implantation on the exfoliation efficiency of H implanted Si. For this purpose, the fluence of H ions was fixed at $4.5 \times 10^{16}\ \mathrm{cm}^{-2}$ (HH) while the fluences of O ions were $5 \times 10^{15}\ \mathrm{cm}^{-2}$ and $1 \times 10^{16}\ \mathrm{cm}^{-2}$ (LO and HO), respectively. Second, the internal micro-defects in O and H co-implanted Si were investigated. Because the large area of

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* Corresponding author. Tel./fax: +86 22 28117054.
E-mail address: wangzhuo@tute.edu.cn (Z. Wang).

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surface exfoliation on Si could seriously affect the observation of micro-defects, adjustments have been made to the fluences of O and H ions to avoid the surface damage. The fluence of H ions reduced to $3.5 \times 10^{16}\,\mathrm{cm}^{-2}$ (LH) and the fluence of O ions was $1 \times 10^{16}\,\mathrm{cm}^{-2}$ (HO). The total Si samples with detailed implant conditions are shown in Table 1. After implantation, the wafers were cut into small pieces for the measurements of various techniques. Before the analyses, the sample pieces were isochronally annealed under a flow of N_2 gas for 1 h. The annealing temperatures range from 300 to 800 °C.

Optical microscopy (OM) was used to investigate the surface damage of implanted and annealed Si samples. Moreover, cross-sectional transmission electron microscopy (XTEM) was performed to identify the implantation induced defect microstructures. XTEM samples were prepared in the conventional way by mechanical thinning and Ar ion etching. The XTEM images were recorded on a Tecnai G2 F20 S-Twin microscope with an acceleration voltage of 200 kV.

3. Results and discussion

OM observations obtained on H-only implanted as well as O and H sequentially implanted Si samples after subsequent annealing are shown in Fig. 1. It should be mentioned that, no surface damage has been found for Si samples implanted with a lower H fluence (LH samples: LH and HO + LH) even after annealing in the temperature range up to 800 °C. However, for three HH samples (HH, LO + HH and HO + HH), the formation and morphology of Si surface damage were strongly dependent on both annealing temperature and the O fluence. At 400 °C annealing, no surface damage was seen on samples HH and LO + HH. As an example, Fig. 1(a) shows the surface morphology of Si implanted with H ions at a fluence of $4.5 \times 10^{16}\,\mathrm{cm}^{-2}$ and followed by annealing at 400 °C. Nevertheless, additional O implantation at a higher fluence could give rise to the Si surface blisters after 400 °C annealing, as shown in Fig. 1(b). At 450 °C annealing, all three HH Si samples presented surface damage. It is seen in Fig. 1(c) that serious damage, such as blisters (solid arrow) and localized exfoliations (dashed arrow), was formed on the surface of sample HH. The size of craters from exfoliated regions is about 3.2–12.1 μm. It is obvious that additional lower fluence O implantation made minor difference on surface morphology, as shown in Fig. 1(d). A lot of surface blisters and exfoliations were also present on sample LO + HH. The size of craters distributes in a range of 2.7–11.6 μm. For sample HO + HH, the additional O implantation at a higher fluence resulted in a small increase in the size and number of the craters.

In order to reveal the specific differences between Fig. 1(c) and (d), detailed measurements have been made on the number and size of the exfoliated craters, as shown in Fig. 2. It is clearly seen that the total number of craters on sample HH is about one third more than sample LO + HH. The size of craters on sample HH is mainly between 5–8 μm. Whereas the size of craters on sample LO + HH is concentrated in 6–9 μm. Therefore, the additional O implantation causes the increase in the average size of craters, from 6.6 to 7.4 μm. Compared with the sample HH, the number of craters on sample LO + HH reduces, but the average size increases.

Table 1
Implantation fluences for co-implanted Si (100) samples.

Sample	O fluence ($10^{16}/\mathrm{cm}^2$)	H fluence ($10^{16}/\mathrm{cm}^2$)
HH	0	4.5
LO + HH	0.5	4.5
HO + HH	1	4.5
LH	0	3.5
HO + LH	1	3.5

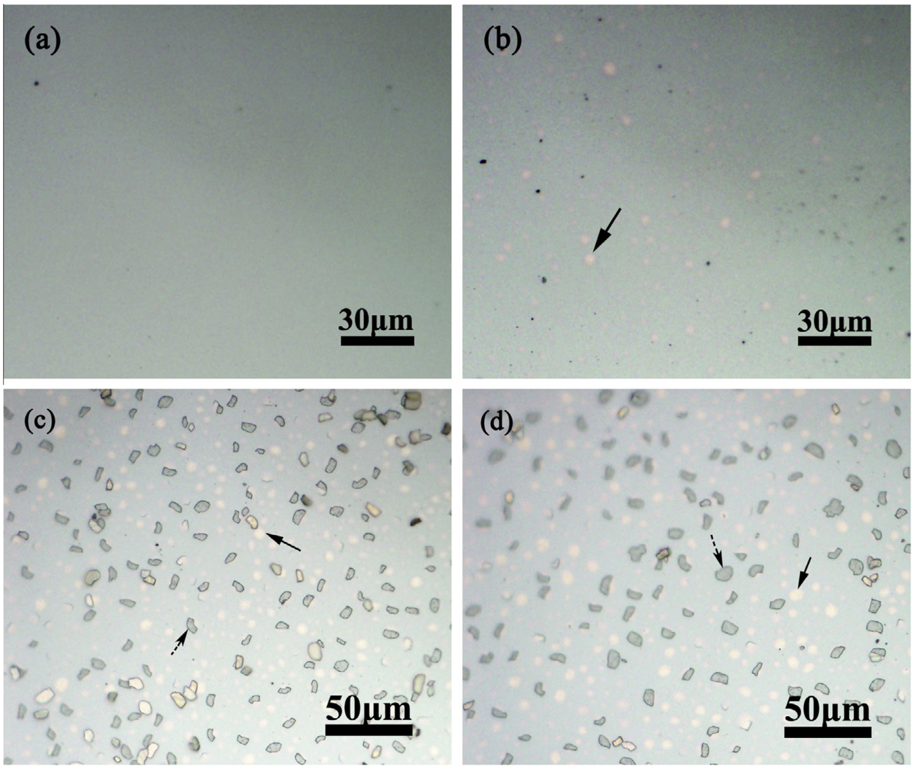

Fig. 1. OM images of Si samples implanted with 190 keV O and/or 40 keV H ions, following different annealing temperatures: (a) HH sample, 400 °C; (b) HO + HH sample, 400 °C; (c) HH sample, 450 °C; (d) LO + HH sample, 450 °C.