Investigation of the inhibiting outdiffusion of erbium atoms to a silicon-on-insulator surface after annealing at high temperature*

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The annealing behaviour of 400 keV Er ions at a fluence of 2×10^{15} cm^{-2} implanted into silicon-on-insulator (SOI) samples is investigated by Rutherford backscattering spectrometry of 2.1 MeV He^{2+} ions with a multiple scattering model. It is found that the damage close to the SOI surface is almost removed after being annealed in O_2 and N_2 atmospheres, successively, at 900 °C, and that only a small number of the Er atoms segregated to the surface of the SOI sample, whereas a large number of Er atoms diffused to a deeper position because of the affinity of Er for oxygen. For the SOI sample co-implanted with Er and O ions, there is no evident outdiffusion of Er atoms to the SOI surface after being annealed in N_2 atmosphere at 900 °C.

Keywords: Er ion implantation, silicon-on-insulator, annealing behavior, Rutherford backscattering technique

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1. Introduction

Research interest in erbium (Er)-doped semiconductors has attracted a great deal of attention,[1−7] as these materials have applications in fiber optics telecommunication systems. The photoluminescence (PL) of Er-doped semiconductors has been widely studied,[8−14] ever since Ennen and Schneider[8] first reported on the observation of 1.54 μm PL due to Er in GaAs and Si. Ion implantation is a unique technique for introducing Er as an impurity into semiconductors. Up until now, the doping of semiconductors with Er has usually been performed by means of ion implantation, with subsequent annealing at high temperatures for the removal of the damage and the activation of the implanted atoms.[15] A restriction of this method is that the radiation defects in the semiconductor are very stable and annealing temperatures about 1000 °C are necessary for good recrystallization.[16] At such a temperature, however, complete recrystallization of the semiconductor is accompanied by segregation of the Er atoms to the surface,[17,18] which would debase Er emission badly. Codoping oxygen (O) with Er into semiconductors is known to enhance both the solubility and the optical activation of Er in semiconductor materials.[19] Thermal diffusion is an effective way of doping O into semiconductors. We expect that annealing at high temperature in an oxygen atmosphere, or Er and O co-implanted in semiconductor materials, is a feasible method of inhibiting the segregation of Er atoms to the semiconductor surface because of the affinity of erbium for oxygen, thereby improving Er luminescence.

Silicon-on-insulator (SOI) waveguide technology is highly promising for future low-cost photonic integrated circuits because of its excellent optical and electronic properties and true compatibility with mature Si CMOS integrated circuit technology. SOI technology is praised as a silicon integrated circuit technology

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in the 21st century. SOI:Er is one of the prospective materials for light sources emitting at 1.54 μm at room temperature (RT). In the present work, we implanted 400 keV Er^+ ions with a fluence of 2×10^{15} cm^{-2} into SOI samples. The annealing behaviour of the SOI sample implanted with Er ions was then investigated. We focused on the feasibility of preventing Er atoms from being segregated to the SOI surface by annealing the sample in oxygen atmosphere at high temperature, and also by co-implanting Er and O into the SOI.

2. Experiment

The SOI wafer used in this study consisted of a 260 nm thick crystal Si (c-Si) cap layer on a 160 nm thick SiO_2 layer, and a 760-μm thick Si substrate. Three SOI samples (named samples I, II, and III) were implanted with Er^+ at a tilted angle of 7° at room temperature at an energy of 400 keV to a dose of 2×10^{15} cm^{-2}. One of the Er ion-doped SOI samples (Sample III) was co-implanted with O ions at an energy of 60 keV to a dose of 1×10^{16} cm^{-2}. The voltage of the implanter, which determined the energy of the implanted ions, was calibrated by a high-tension voltmeter. The incident current density was less than 1 $\mu A/cm^2$ to avoid excessive heating of the samples. An electrostatic scanning system was used in order to ensure uniformity over the implanted area, and conventional furnace annealing was then carried out for the doped SOI samples after implantation. SOI samples I and III were annealed in flowing N_2 atmosphere at 900 °C for 60 min, and SOI sample II was first annealed in flowing O_2 atmosphere at 900 °C for 10 min and subsequently in N_2 at 900 °C for 60 min.

The depth distributions and the lattice disorders in the SOI samples created by Er implantation were analysed by Rutherford backscattering spectrometry and the channeling (RBS/C) technique. RBS/C spectrometry was performed using a 2.1-MeV He^{2+} ion beam generated by a 1.7-MV tandem accelerator with a beam current of around 10 nA. A surface barrier detector at an angle of 165° with respect to the incident beam was used to detect the backscattered articles.

The implantations were performed on an ion implanter at the Institute of Semiconductors, Chinese Academy of Sciences. The RBS/C measurements were carried out at the 1.7-MV tandem accelerator of Shandong University.

3. Results and discussion

Channeling has been shown to be a useful tool for the investigation of the lattice disorder created from the heavy ion bombardment of single crystals.[20] The channeling spectrum not only provides information about the total disorder created by a given implant, but also contains information about the depth distribution of the damage and, in principle, can be used to extract the full depth profile of the lattice disorder.

In Fig. 1, the RBS/C spectra of SOI sample I implanted by 400-keV Er ions with a fluence of 2×10^{15} cm^{-2} at room temperature (as-implanted) and annealed in flowing N_2 atmosphere at 900 °C for 60 min (annealed in N_2) are presented. For comparison, the random and the channeling (virgin) spectra of an undoped SOI sample are also presented in the figure. From Fig. 1, a large broad peak in the top Si surface is observed in the as-implanted spectrum, which indicates that an amorphous layer with a thickness of 150 nm is created by Er^+ implantation. The yields of the damage spectra on the low energy side of these peaks do not decrease to the pre-implantation value and maintain at a relatively high level due to the extra dechanneling. From the spectrum of the sample annealed in N_2, it can be seen that after annealing at 900 °C for 60 min, the amorphous layer is recrystallized, which is indicated by the low yield of the channeling spectrum. The comparison of the spectrum in the surface Si area between the annealed and virgin samples shows that the defects still exist after annealing at 900 °C. From Fig. 1, it can be observed

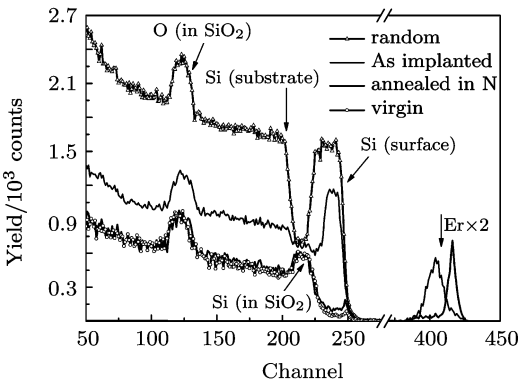


Fig. 1. RBS/C spectra of SOI sample I implanted by 400-keV Er with a fluence of 2×10^{15} cm^{-2} at room temperature and annealed in N_2 atmosphere at 900 °C for 60 min.

that Er atoms diffused and segregated at the surface during annealing, which are indicated by the higher and narrower Er spectra at larger channel numbers,

which is similar to the reported results of Er in SiC and GaAs.[8,21] An analysis shows that the total number of Er atoms remaining in the sample is 41% lower than that in the as-implanted sample after annealing at 900 °C in N_2 atmosphere.

Figure 2 shows the RBS/C spectra of SOI sample II implanted by 400-keV Er ions with a fluence of 2×10^{15} cm^{-2} at room temperature, followed by two-step annealing first in O_2 and then N_2 atmospheres, both at 900 °C. For comparison, the as-implanted channeling spectrum of the SOI sample II and the virgin spectrum of SOI are also shown in Fig. 2. It can be seen from the spectrum of SOI sample II that the spectrum shape of the SOI sample in the surface Si area after annealing in O_2 and N_2 gas atmospheres is different from and higher than its aligned virgin spectrum: an O peak (with a width approx. 190 nm) and an evidently disordered Si peak (with a width of about 60 nm) appears. This means that the damage around the Si surface has been almost removed after annealing at 900 °C, and the disordered region has moved to a deeper place and become much smaller. The O atoms also reach a relatively deeper position in the SOI sample by thermal diffusion, and only a small number of Er atoms have segregated into the surface of the sample; lots of Er atoms have diffused to deeper positions because of the affinity of Er for oxygen. Analysis shows that the total number of Er atoms remaining in the sample after annealing at 900 °C in O_2 and N_2 atmospheres is about 4% lower than that in the as-implanted sample. In view of these facts, it is considered that annealing in oxygen atmosphere can inhibit the segregation of Er from SOI at elevated annealing temperatures.

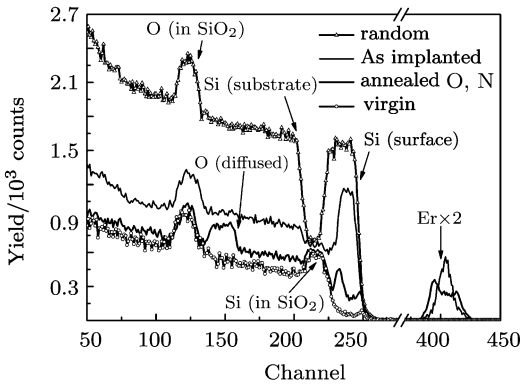


Fig. 2. The RBS channeling spectra for SOI sample II implanted by 400-keV Er with a fluence of 2×10^{15} cm^{-2} at room temperature and annealed in O_2 and N_2 atmospheres, successively, at 900 °C.

Figure 3 shows the RBS/C spectra for SOI sample III co-implanted by 400-keV Er and 60-keV O ions at room temperature (as implanted) and annealed in N_2 atmosphere at 900 °C for 60 min (annealed in N), respectively. The random and the channeling (virgin) spectra of the undoped SOI sample are also shown in the figure. It can be observed from the spectra that after annealing at 900 °C for 60 min, the shape of its aligned spectrum is similar to that of the aligned as-implanted spectrum, but the damaged peak is much lower and thinner than that in the as-implanted spectrum. The maximum damage ratio falls to around 10%, which means that the re-crystallization of the surface Si layer of SOI is not perfect after annealing at 900 °C for 60 min, and the damage in the implanted sample has not been eliminated completely. The Er distribution after annealing is almost the same as that before annealing (the right part of Fig. 3). Unlike the case where only Er ions are implanted into SOI sample I, the re-crystallization of the surface Si of SOI sample III after annealing at 900 °C is not accompanied by the segregation of Er to the surface because of erbium's affinity for oxygen. So this is another way to prevent Er atoms from outdiffusing into the SOI surface by co-implanting Er and O into the SOI.

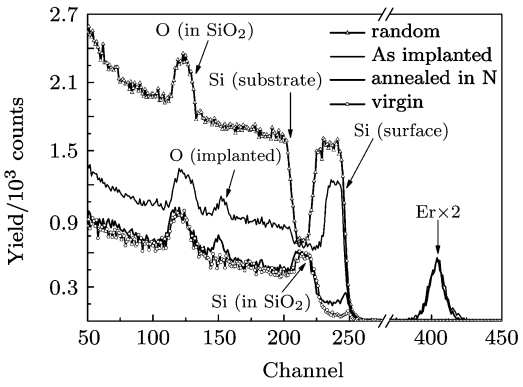


Fig. 3. RBS/C spectra for SOI sample III co-implanted by 400-keV Er and 60-keV O ions at room temperature and annealed in N_2 atmosphere at 900 °C for 60 min.

4. Summary

The annealing behaviour of an SOI sample implanted with Er ions is investigated by the Rutherford backscattering technique. The damage around the Si surface in the SOI sample is almost removed after annealing in N_2 atmospheres at 900 °C. Recrystallization of the surface Si of the SOI sample after annealing at 900 °C is accompanied by strong segregation of Er to the SOI surface. For the SOI sample annealed in

O_2 and N_2 atmospheres successively at 900 °C, only a very small number of the Er atoms segregate to the surface of the SOI sample, and lots of Er atoms diffuse to deeper positions because O atoms reach relatively deep positions in the surface Si layer by thermal diffusion. For the Er and O co-implanted SOI sample, no Er atoms are segregated to the surface of SOI. So we conclude that it is feasible to prevent Er atoms from segregating into the SOI surface by annealing in oxygen atmosphere or by co-implanting Er and O into the SOI sample.

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