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Neutron-enhanced annealing of ion-implantation induced damage in silicon heated by nuclear reactions

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ABSTRACT

The effect of neutron irradiation on recovery (annealing) of irradiation damage has been investigated for self-ion implanted Si. A damage layer was introduced by 200 keV Si^+ implantation to a fluence of 5×10^{14} Si/cm^2 at room temperature. The damaged samples were neutron-irradiated to 3.8×10^{19} n/cm^2 (fast neutron), without intentional heating, in the core of the Kyoto University Reactor. During neutron irradiation, the samples were heated only by nuclear reactions, and the irradiation temperature was estimated to be less than 90 °C. The damage levels of the samples were characterized by Rutherford backscattering with channeling. Reduction of damage peaks as a result of neutron irradiation was clearly observed in the samples. The annealing efficiency was calculated to be 0.44 defects/displacement.

1. Introduction

Ion implantation techniques have been widely used to control dopant concentrations in various semiconductor devices. Since the irradiation of energetic ions inevitably induces irradiation damage in crystalline lattices, the recovery (annealing) of such irradiation damage has been a primary focus of ion implantation research. On the other hand, some studies have shown that ion irradiation under appropriate conditions (e.g., irradiation temperature, energy and flux) reduces preexisting implantation-induced damage. One example is recovery of heavy implantation-induced disorder by ion beam irradiation [1–5]. Another example is ion-beam induced epitaxial crystallization (IBIEC) of amorphous layers [6–9].

The mechanism of ion beam induced recovery of irradiation damage is not yet fully understood [8,9], but the energy transfer through nuclear energy deposition or atomic displacement has been found to be a key factor in determining annealing rates. As one approach to elucidating the phenomenon, electron-beam induced epitaxial crystallization (EBIEC) was examined [10,11]. Interestingly, EBIEC occurred even at cryogenic temperatures [10], while IBIEC occurred only at elevated temperatures. These results suggest that the use of different types of energetic particles may provide insight into the mechanism behind ion-beam annealing effects. With this in mind, neutron-enhanced annealing was investigated in our previous study [12]. The initial distributions of Frenkel pairs formed by ion, neutron and electron irradiation of solids are different. The collision cascades formed in samples by ion irradiation are located near the projected ranges (Bragg peaks), while those formed by neutron irradiation are uniformly distributed. Electrons in EBIEC experiments typically form isolated Frenkel pairs (not collision cascades). Moreover, electronic excitation is much greater in the case of electron irradiation than in that of ion or neutron irradiation. Thus, we would expect different annealing behaviors based on such different defect formation processes. In this study, we performed neutron irradiation at lower temperature, in comparison with the previous study at 400 °C [12], to investigate the temperature dependence of the annealing process.

2. Experimental procedure

A Czochralski-grown (100)-oriented Si wafer (p-type, B-doped, 8–12 Ω cm) was used as a substrate. A damage layer was introduced by 200 keV Si^+ implantation to a fluence of 5×10^{14} cm^{-2} at room temperature. The implantation of self ions (Si^+) was chosen in order to avoid impurity effects from the implanted ions.

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The ion beam was scanned over the substrate for uniform irradiation. The Si-implanted substrate was cut into small samples, some of which were then wrapped in Al foil, encapsulated in an Al capsule with He ambient gas, and neutron irradiated for 12 weeks in the core irradiation facility of the Kyoto University Reactor (KUR) operating at 5 MW [13]. The nominal neutron flux was 6.3×10^{13} n/cm^2 s (1.4×10^{13} n/cm^2 s for fast neutrons). Typical irradiation periods for one week were around 70 h. The total fast neutron fluence was 3.8×10^{19} n/cm^2. A control sample was thermally annealed at 90 °C in a quartz tube furnace in Ar gas atmosphere for the same period as the neutron irradiation.

The damage levels of irradiated or thermally annealed samples were characterized by Rutherford backscattering/channeling (RBS/C) using 2 MeV He ions at a scattering angle of 135°, primarily at the Wakasa Wan Energy Research Center [14]. Depth scales were calculated by using stopping powers for the channeled ions. The atomic displacements by neutron and ion irradiation were calculated by the SPECTER [15] and SRIM [16] codes, respectively. The displacement energy of Si was assumed to be 13 eV in the calculation [10].

3. Results and discussion

KUR is a light-water moderated nuclear reactor dedicated to research purposes. The light-water temperature in the core tank was typically 45–50 °C during operation. The samples in the Al capsule were heated above the water temperature by nuclear reactions (mainly gamma-ray absorption). The sample temperature of the core irradiation facility cannot be directly measured during reactor operation. Thus, temperature measurements during irradiation have been performed using several types of Ti–Ni shape-memory alloys and thermo labels on an Al plate at various positions in the capsule [13,17]. Maximum temperatures, depending on different irradiation runs, were estimated to be 85–90 °C from the shape-memory alloys [13]; a temperature at the center of the capsule was estimated to be 80–85 °C from the thermo labels [17]. Note that the neutron flux, which is closely related to temperature, was position dependent in the capsule. Thus, the samples in this study were placed at the center of the capsule to expose them to average neutron flux.

In addition, we estimated the sample temperature by solving a partial differential equation describing the heat flow inside the Al capsule as shown in Appendix. Fig. 1 shows the temperature increase inside the irradiation capsule, for three different nuclear heating conditions (0.24, 0.36 and 0.49 W/g). The temperature increased immediately after commencing irradiation, and almost saturated within 1000 s. The result in Fig. 1 corresponds to the temperature after saturation (i.e., $\partial T/\partial t = 0$). Even in the case of the highest nuclear heating (0.49 W/g), the temperature was below 90 °C. This result was consistent with the values measured by the shape-memory alloys and thermo labels. Since the thermal annealing rate for heavily damaged Si was nearly constant around 90 °C [18], we thermally annealed the control sample at 90 °C.

Fig. 2 shows the RBS/C spectra of the as-implanted, thermally annealed and neutron-irradiated samples. A damage peak formed near the end of range for 200 keV Si$^+$ as shown by the as-implanted sample. The damage peak of the thermally annealed sample was slightly lower than the peak of the as-implanted sample, while the damage peak of the neutron-irradiated sample was significantly lower than the peak of the thermally annealed sample. This indicates the enhancement of damage annealing (recovery) caused by neutron irradiation. Neutron irradiation slightly increases the aligned backscattering yield in the crystalline Si without ion implantation (open triangles in Fig. 2), but the annealing effect of neutron irradiation counteracts this damaging effect; and in the present study, the annealing effect exceeded the damaging effect.

Fig. 3 shows the disorder profiles, obtained by dechanneling calculation, for the damage peaks in the RBS/C spectra of Fig. 2. Dechanneling fractions were subtracted, ignoring the neutron damage in the crystalline region deeper than the ion damage layer. The number of disordered atoms in the neutron-irradiated samples was clearly less than that in the as-implanted and thermally annealed samples. From the peak height difference between the thermally annealed and neutron-irradiated samples, the number of atoms annealed by neutron irradiation, meaning those that were recovered from disordered to ordered (lattice) sites, was calculated to be 3.1×10^{21} cm^{-3}. Using the SPECTER code, the number of atoms displaced by neutron irradiation was calculated to be 0.14 dpa. When the annealing efficiency is defined as the ratio of annealed atoms to atoms displaced by neutrons, the annealing efficiency obtained in this study is 0.44 defects/displacement. We note that the number of atoms displaced by gamma-ray irradiation was negligible, as calculated in our previous study [12]. The width of the damage peak decreased, in addition to the decrease in peak height. This suggests that the lightly damaged regions at the tails of the damage peak were more easily annealed than the heavily damaged region near the damage peak. This behavior is similar to that of IBIEC of buried amorphous layers, but the damage layer was not fully amorphized and the epitaxial crystallization effect was much weaker than the disorder annealing effect in the

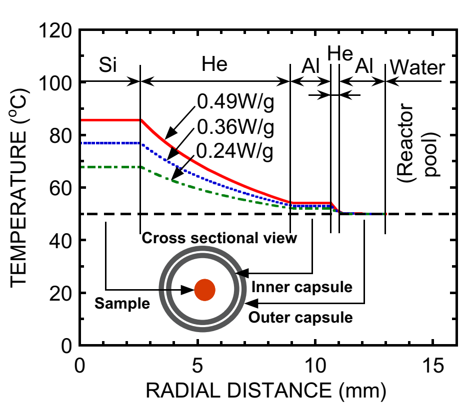

Fig. 1. Calculated temperature inside the irradiation capsule under three different gamma-ray heating conditions. The illustration in the figure shows a cross section of the irradiation capsule assumed in the calculation.

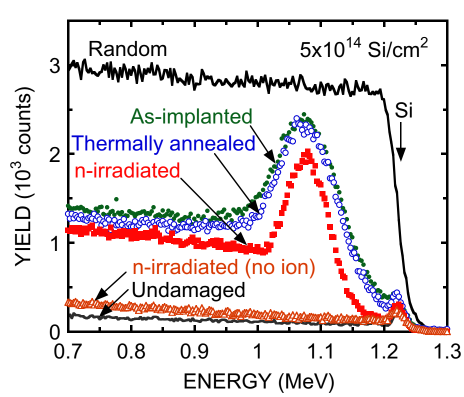

Fig. 2. RBS/C spectra indicating the effect of neutron irradiation on a damage peak introduced by self-ion implantation. The sample after ion implantation and neutron irradiation (closed squares) was compared with as-implanted (closed circles) and thermally annealed (open circles) samples, and with a neutron irradiated sample without ion irradiation (open triangles).