2.11 POSITRON ANNIHILATION STUDY ON DEFECTS IN ION-IMPLANTED Si

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Abstract

Two-detector coincidence measurements of the Doppler broadened annihilation spectra with a variable energy positron beam are carried out for the study of the annealing behavior of Si implanted with As, P, Cu and H ions. In P-implanted Si, growth of the defect complexes are observed in coincidence Doppler broadening spectra up to 400°C. In Cu-implanted Si, the formation of defect-Cu complexes is indicated. In H-implanted Si, the passivation effect of hydrogen on positron traps are observed in the low temperature region up to 400°C.

Keywords: Positron beam, Doppler broadening, Defects, Si, Ion implantation

1. Introduction

The doping of semiconductors by the process of ion implantation has been widely used in the fabrication of integrated circuits. Detailed knowledge on defects induced by ion implantation and their annealing behavior are of great technological importance. The variable energy positron beam has been proven to be unique tool for studying near surface defects in solids. Coincidence detection of annihilation photons with two Ge detectors can eliminate random background and yield good signal-to-noise ratio in Doppler broadening measurements, especially for high momentum region, where the core electron contribution is large.[1] Thus, coincidence Doppler broadening(CDB) measurements are expected to provide additional information about the atoms surrounding the annihilation site.[2] In the present study, we have applied this technique with a variable energy positron beam to study annealing process of defects induced in Si by implantation of As, P, Cu and H ions.

2. Experiments

The Doppler broadening of the annihilation radiation was measured with two Ge detectors. The energy resolutions of detectors are 2.0 keV and 2.4 keV(FWHM) for the 1.33 MeV gamma ray of ^{60}Co. Positrons from ^{22}Na source were moderated with W single crystal foil or W mesh and guided magnetically to the specimen. Coincidence count rate was about 300/s

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and more than 10^7 counts were accumulated for each spectrum. Ion implantation was carried out on p-type 10Ωcm Si(100) crystals grown with Czochralski (Cz) method. Implantation conditions for each ion are shown in Table 1. After implantation, the samples were annealed in N_2 atmosphere for 30 min at various temperature. In CDB measurements, positron energies were fixed with values shown in Table 1. Conventional Doppler broadening measurements with single detector were also carried out with varying the positron energy.

Table 1. Ion implantation condition and positron energy in CDB measurements.

Ion	Implantation energy	Dose	Positron energy
As	100 keV	2 x 10^{14}/cm^2	2.5 keV
P	100 keV	2 x 10^{14}/cm^2	3 keV
Cu	140 keV	2 x 10^{14}/cm^2	4 keV
H	60 keV	1 x 10^{16}/cm^2	6 keV

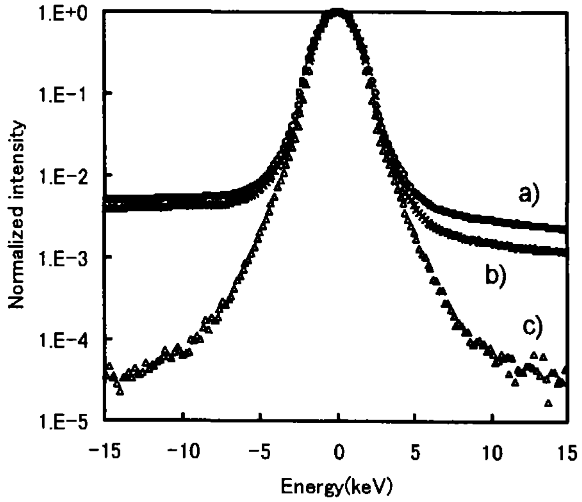

Fig. 1 The measured energy spectrum under different conditions. a):conventional Doppler broadening spectrum with one detector. b): one-detector spectrum with coincidence condition. c): diagonal cross section of CDB spectrum.

3. Results and discussion

The measured Doppler broadening spectrum under different condition are shown in Fig. 1. The diagonal cross-section of the two-dimensional CDB spectrum has two orders of magnitude better signal-to-noise ratio compared with conventional Doppler broadening spectrum obtained with single detector. The CDB spectra for Si implanted with As are shown in Fig. 2. They are depicted as the ratio to bulk Si as the momentum distribution extends over several orders of magnitude and small but significant difference may be obscured with a normal plot. S versus W plot of CDB spectra are shown in Fig. 3. Here, S stands for the low momentum component up to 2.5×10^{-3} m_0c. W is for high momentum component from 8×10^{-3} m_0c to 15×10^{-3} m_0c. Comparison between experimental data shown in Fig. 2 and calculation for divacancy[3] indicates that divacancy is the dominant defect in as-implanted Si, which is consistent with the result of earlier experiments[4]. Only

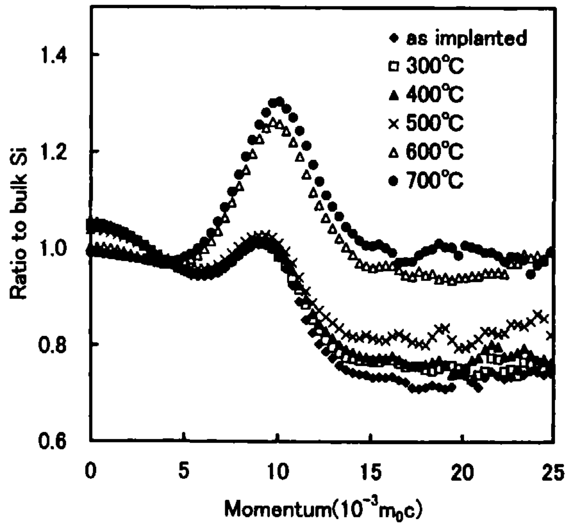

Fig. 2 CDB spectra for Si implanted with As

small changes of the CDB spectra are observed up to 400°C. Pronounced peak around 10×10^{-3} m_0c appears after 600°C annealing. The origin of this structure is not known at present. Peaks around this region come from difference between rapidly decreasing momentum distribution around Jones zone in crystalline Si and slowly varying momentum distribution of localized electrons.[3] Positrons trapped at V-O complexes are known to give a peak around 10×10^{-3} m_0c. Conventional S parameter measurements, though, show no peak for the sample annealed at 600°C. In the present experiments, V-O complexes may not be the origin of these peaks. The other possible candidate is the positrons annihilating on the sample surface. By annealing, diffusion length of positrons becomes larger. The provability for positrons injected with a fixed energy can reach surface is increased.

The CDB spectra for Si implanted with P are shown in Fig. 4. S-W plot of CDB spectra are shown in Fig. 3 with those for Si implanted with As. Close resemblance is seen between as-implanted samples for both ions. It supports that the dominant defect in as-implanted Si is divacancy. In the early stage of the annealing up to 400°C, though, annealing behavior is somewhat different. In case of P implantation, S becomes larger with annealing temperature, which indicates divacancies agglomerate to larger vacancy complexes. It is unlikely that oxygen atoms in Cz-Si are involved in these vacancy complexes because CDB spectra around 10×10^{-3} m_0c shows very small changes up to 500°C. Annealing at 600°C increases the peak around 10×10^{-3} m_0c with the still high S value, which may indicate the formation of V-O complexes.

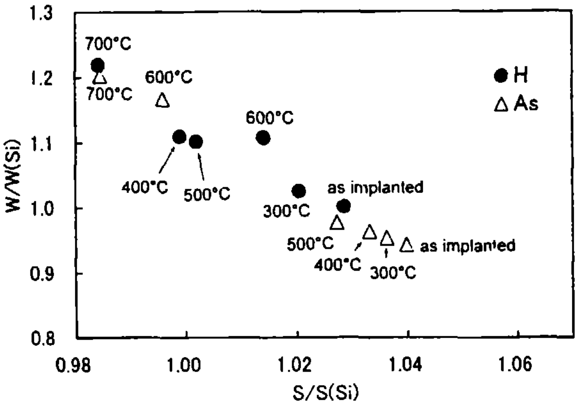

Fig. 3 S-W plot of CDB spectra for Si implanted with As and P. Data labels are annealing temperature.

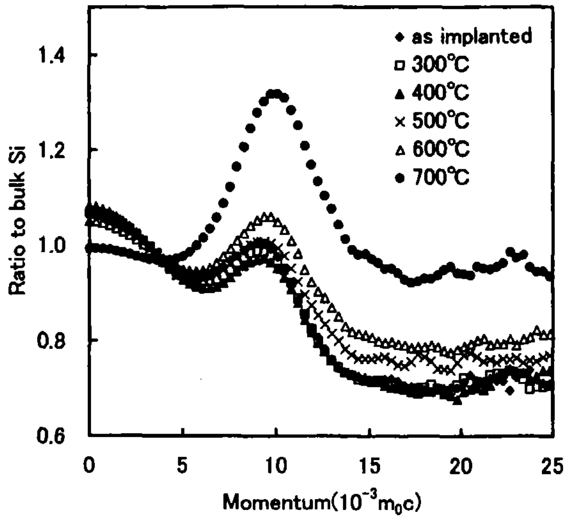

Fig. 4 CDB spectra for Si implanted with P.

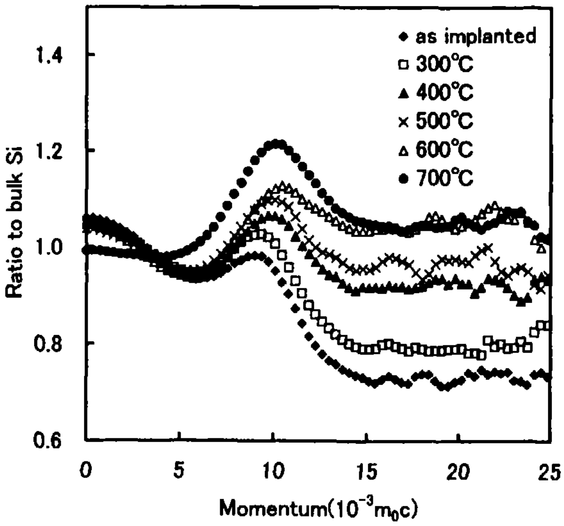

Fig. 5 CDB spectra for Si implanted with Cu.

The CDB spectra for Si implanted with Cu are shown in Fig. 5. Annealing behavior is quite different in case of Cu implantation compared with As and P. Shape of the CDB spectrum for as-implanted state is similar with the case of As and P. Again it indicates that large part of positrons are trapped at divacancy. Evolution of defects starts at lower temperature. High momentum component above $15\text{x}10^{-3}$ m_0c in CDB spectra become larger with low temperature annealing compared with the case of As and P. Also peak position and shape are different, which indicate that some part of trapped positrons annihilate with other element than Si. The CDB spectrum for annealed Cu is shown in Fig. 6 as the ratio to that for Si. The CDB spectrum for Cu has larger high momentum component over about $10\text{x}10^{-3}$ m_0c because Cu has larger core than Si. The CDB spectra for Cu-implanted Si annealed at 600°C and 700°C have larger high momentum components, which may come from annihilation with Cu core electrons. It is provable that Cu atoms exist in vacancy complexes.

The CDB spectra for H-implanted Si are shown in Fig. 7. The results of conventional Doppler broadening measurements are shown in Fig. 8. The CDB spectrum is different from those for As and P even as-implanted state. Annealing is considered to be performed with at least three steps. Peaks in the conventional S parameter measurements, which reflect the distribution of positron trap site, are seen in near surface region than expected from the range of H ion up to 300°C.[5] It indicates that the defects induced around the range of H ion are at least partly passivated with H ion

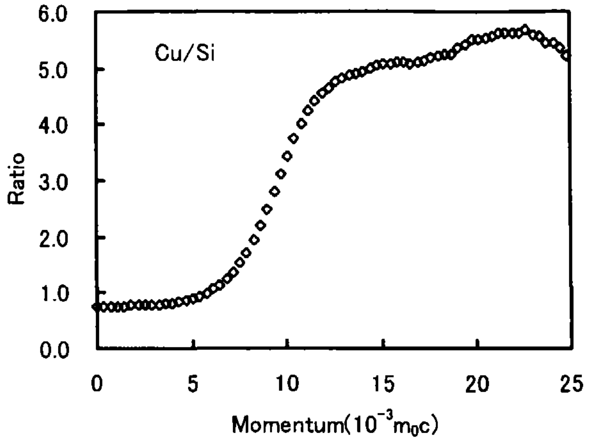

Fig. 6 CDB spectrum for pure Cu shown as the ratio to that for Si.

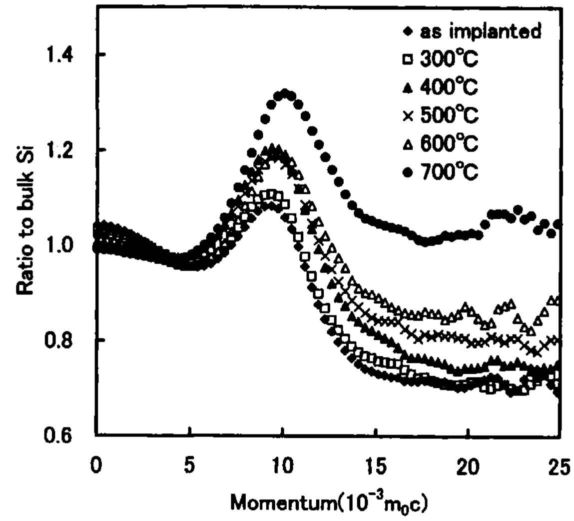

Fig. 7 CDB spectra for Si implanted with H.

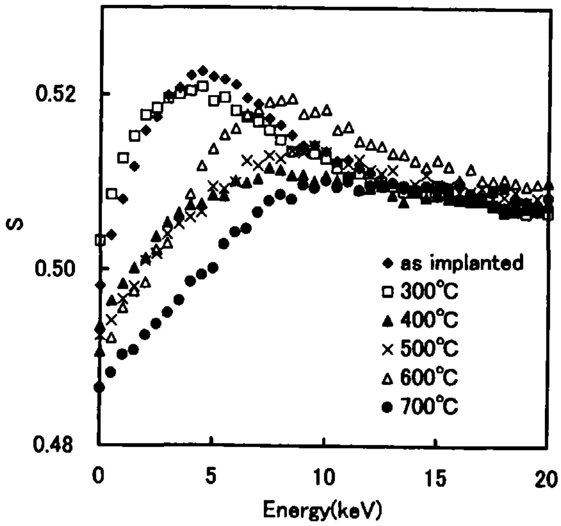

Fig. 8 S-parameter of conventional Doppler broadening spectra for Si implanted with H.

itself.[6] From 400°C to 600°C, these hydrogens are released, which results in increase of S parameter while the CDB spectra in high momentum region do not change much. These defect complexes are annealed out at higher temperature.

In conclusion, different annealing behavior of Si implanted with various kinds of ions is shown with CDB measurements. CDB measurement is a powerful tool for investigation of defects. Though, combination with other techniques such as lifetime, conventional Doppler broadening measurements, first principle calculation is necessary for full utilization of CDB measurements.

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