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Annealing Process of Defects in Epitaxial SiC Induced by He and Electron Irradiation: Positron Annihilation Study

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Abstract

Annealing processes of vacancy-type defects in epitaxial 6H SiC after 2 MeV electron irradiation and multiple He implantation have been investigated using positron annihilation spectroscopy. Vacancy-type defects are found to disappear in two annealing stages: at 500-800°C and 1200-1500°C. Silicon vacancies are the major positron trapping centers after electron irradiation. Two annealing stages after electron irradiation are attributed to the disappearance of isolated silicon vacancies and complexes associated with silicon vacancies, respectively. In He-irradiated SiC, divacancies are also generated in addition to silicon vacancies.

Introduction

Radiation-induced defects in SiC are of great importance from both fundamental and technological viewpoints. In SiC device processing, ion implantation is indispensable for the selective doping because of small diffusion coefficients of dopants in this material. To enhance the electrical activity of implanted dopants, defects induced by implantation should be removed. Electron irradiation is also used for the control of minority carrier lifetime. Electrical devices based on SiC tend to be fabricated using high-quality epilayers. It is therefore important to identify defects in SiC epilayers induced by irradiation and to clarify their thermal stability.

In deep level transient spectroscopy (DLTS) measurements, several deep levels termed $E_1/E_2(E_C$-0.39~0.43 eV), $RD_5(E_C$-0.43~0.47 eV), $Z_1/Z_2(E_C$-0.65~0.72 eV) and $R(E_C$-1.17~1.27 eV) centers are commonly seen in 6H SiC epilayers after fast-particle irradiation [1-5]. These defects are significantly reduced by heat treatment up to 1700°C [1, 2]. The photoluminescence (PL) D_1 spectrum is also a main center observed after irradiation and subsequent heat treatment [6]. The complementary study using DLTS and PL [2] suggests that E_1/E_2 levels and D_1 centers are originating from the same defect species. The origins of these deep levels are however still open questions. Optically detected magnetic resonance (ODMR) studies show the generation of silicon vacancies after electron irradiation and their annealing at around 750°C [7].

Positron annihilation spectroscopy is a suitable method to investigate vacancy-type defects in semiconductors [8]. Using the positron beam technique, defects in thin films can also be detected. We performed annealing experiments for 6H SiC epilayers after He implantation and electron irradiation. In this report, we show the annealing characteristics of vacancy-type defects.

Experimental

Samples used in this study are cut from a high-quality 6H SiC epilayer (4.9 μm thick) doped with nitrogen (n-type: n=4x10^{15}cm^{-3}). As a reference, we also used p-type epitaxial SiC. They were subjected to 2 MeV electron irradiation with a dose of 3x10^{17}e$^-$/cm^2 and He implantation at room temperature. In the He implantation, an eight-fold implantation with energies from 30 to 950 keV

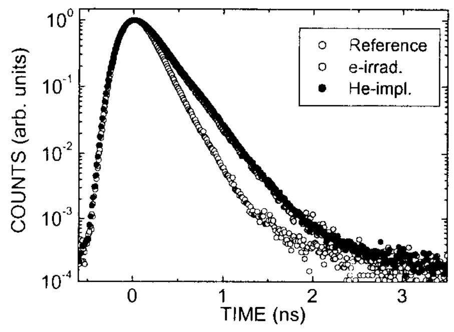

Fig. 1 Positron lifetime spectra obtained at E=17 keV. The reference spectrum is measured with unirradiated p-type specimen.

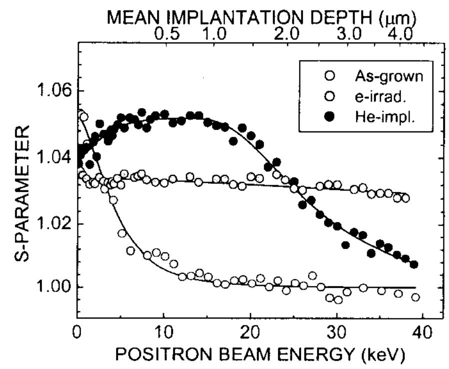

Fig. 2 S-parameters (normalized) as a function of positron beam energy. Solid lines are the results of VEPFIT analysis.

and doses from 8.0×10^{11} to 1.3×10^{12} He^+/cm^2 was carried out to form a box-shaped damage profile with a maximum depth at 2.4 μm. After irradiation, isochronal annealing was done from 100 to 1700°C for 30 minutes. Using a monoenergetic positron beam, Doppler broadening measurements were performed at room temperature after each annealing. Positron annihilation parameters called S and W, which are defined as peak and tail areas [8], respectively, of Doppler spectrum, were calculated. To see the change of dominant defect species during annealing, S-W correlation was also examined. Positron lifetime measurements were performed with a 17 keV positron beam. The average lifetime was determined.

Results and Analysis

Figure 1 shows positron lifetime spectra for the reference (unirradiated p-type) and irradiated samples. The average positron lifetime for the reference sample is 140 ps. This is in good agreement with the bulk lifetime reported so far. Positron lifetimes clearly increase after irradiation showing the presence of vacancy-type defects. The average lifetimes for the electron-irradiated and He-implanted samples are 197 ps and 212 ps, respectively. Figure 2 shows S-parameters as a function of positron beam energy E. Here, S-parameters are normalized to the bulk value. For the unirradiated sample (n-type), S-parameter is almost constant at E>15 keV. This shows that most positrons annihilate in perfect region. The increase in S-parameter in low energy region is due to surface effects. For the electron-irradiated sample, S-parameter is almost constant up to E=39 keV indicating the homogeneous vacancy distribution. For the He-implanted sample, S-parameter is greater than that of the unirradiated sample below 20 keV and decreases at higher energies. The VEPFIT [9] analyses were made with a uniform and a box-shaped defect distribution for the electron-irradiated and He-implanted samples, respectively. The results of fitting are also shown in Fig. 2. For the He-implanted sample, the layer boundary of defect region determined by the analysis agrees well with

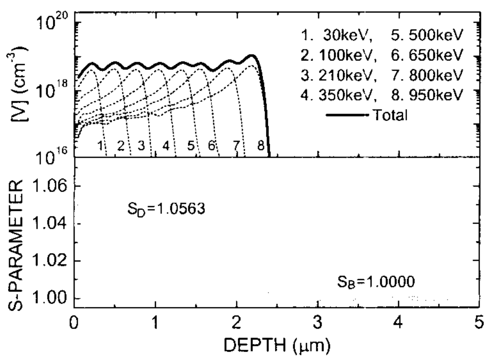

Fig. 3 Distributions of S-parameter for the He-implanted sample from VEPFIT analysis and vacancies from SRIM simulation [10].

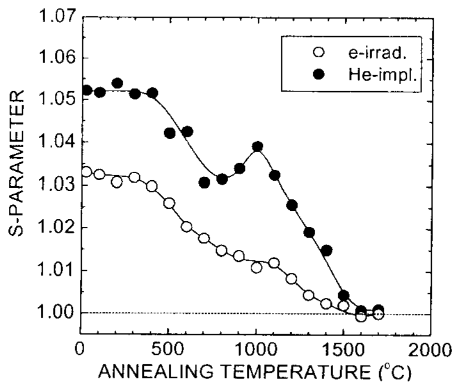

Fig. 4 Annealing behavior of *S*-parameters in defect region obtained from VEPFIT analysis.

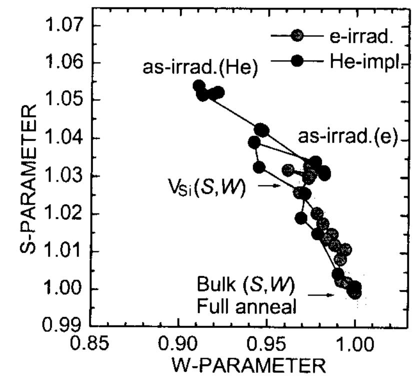

Fig. 5 *S-W* plot. Grey regions show (*S*,*W*) for silicon vacancies and bulk. (*S*, *W*) for bulk coincides with fully annealed state.

that obtained from the SRIM simulation [10] (Fig. 3). Annealing behavior of *S*-parameters is shown in Fig. 4. For both the electron-irradiated and He-implanted samples, two annealing stages appear at 500-800°C and 1200-1500°C. The *S*-parameter approaches the unirradiated state until 1700°C. For the He-implanted sample, *S*-parameter tends to increase from 800°C to 1000°C before the second annealing stage. The *S-W* correlation is also shown in Fig. 5. In this figure, *S* and *W* parameters for silicon vacancies determined previously [11,12] are also displayed.

Discussion

A. *Electron irradiation*

The lifetime of positron at a silicon vacancy was experimentally determined to be 188 ps for 3C SiC at room temperature [13]. Theoretical positron lifetimes for a carbon vacancy, a silicon vacancy and a divacancy are reported to be about 153 ps, 194 ps and 214 ps, respectively [14]. The average lifetime for the electron-irradiated sample (197 ps) is close to the positron lifetime for silicon vacancies. Thus, silicon vacancies are considered to be the major positron trapping centers. Divacancies may also be generated. Considering that the displacement energy for SiC is about 30 eV [15], the average primary knock-on atom energy for 2 MeV electron irradiation is 70-80 eV. The concentration of divacancies is therefore expected to be much smaller than that of silicon vacancies. Carbon vacancies are also primary defects and stable at room temperature [16]. However, since the positron lifetime for a carbon vacancy is fairly close to the bulk lifetime, carbon vacancies may have a minor effect. As seen from the *S-W* plots (Fig. 5), before annealing *S* and *W* for the electron-irradiated sample is located in the region for silicon vacancies. In addition, almost one straight correlation is found until the full annealed state. These also indicate that silicon vacancies are the major defects and the concentration decreases upon annealing.

It is known that silicon vacancies in 3C SiC are mobile above 600°C [17]. Carbon vacancies disappear below 300°C [16]. It is also shown that the density of silicon vacancies in epitaxial 6H SiC drastically decreases after the annealing at 750°C by ODMR [7]. The first annealing stage at 500-800°C is consistently explained as the disappearance of isolated silicon vacancies. Above 1000°C, only one annealing stage appears suggesting one type of defects act as positron trapping centers. The annealing stage at 1200-1500°C is attributed to the disappearance of complexes associated with silicon vacancies, which have higher thermal stability than isolated silicon vacancies [12,18]. In electron-irradiated epitaxial 6H SiC, only E_1/E_2 levels are reported to remain after annealing at 1000°C and these levels drastically decrease above 1400°C [3]. Thus, it is possible to assign the E_1/E_2 levels to complexes related to silicon vacancies.

B. *He implantation*

For the He-implanted sample, the average lifetime is 212 ps. This is greater than the positron lifetime for silicon vacancies. The *S*-parameter for the He-implanted sample is also greater than that for silicon vacancies. Probably, in the He-implanted sample, divacancies are also important positron trapping centers in addition to silicon vacancies. The He-implanted sample also shows two annealing stages at 500-800°C and 1200-1500°C. From the *S*-*W* plots (Fig. 4), it is found that dominant defect species changes above 800°C. The *S*-*W* correlation above 1000°C approaches the line between silicon vacancies and bulk. Probably, divacancies and isolated silicon vacancies are annealed up to 800°C. Divacancies are considered to disappear due to the recombination with interstitials [17,18]. Above 800°C, complexes including silicon vacancies are major defects and they disappear up to 1700°C as well as the electron-irradiated sample. The increase of *S*-parameter at 800-1000°C indicates the formation of this defect due to annealing.

According to the DLTS experiments for He-implanted epitaxial 6H SiC, the annealing temperatures of RD_5 and R levels are reported to be 100-500°C and 500-1000°C, respectively [1]. The Z_1/Z_2 level disappears in rather broad range from 100°C to 1400°C [1,2]. The concentration of E_1/E_2 levels increases at around 700°C and drastically decreases at 1200-1400°C [2]. It seems that the decrease in the *S*-parameter until 800°C coincides with the annealing of RD_5 and R levels. The annealing characteristics of *S*-parameter above 800°C is similar to that of E_1/E_2 levels. Thus, the E_1/E_2 levels are possibly originating from vacancy-type defects.

Summary

In summary, we studied annealing processes of vacancy-type defects in epitaxial 6H SiC after electron irradiation and He implantation. Two major annealing stages at 500-800°C and 1200-1500°C related to vacancy-type defects are detected. It was found that silicon vacancies are the main positron trapping centers in the electron-irradiated SiC. In the He-implanted sample, divacancies are also comparable positron trapping centers to silicon vacancies. Vacancy-type defects were no longer detected after the annealing at 1700°C.

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