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Physica B 308–310 (2001) 660–663

PHYSICA B

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# Vacancies in He-implanted 4H and 6H SiC epilayers studied by positron annihilation

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## Abstract

Defects in epitaxially grown 4H and 6H SiC induced by He-implantation have been studied by positron annihilation and deep level transient spectroscopy. Two major annealing processes of vacancy-type defects appeared at 500–800°C and above 1000°C irrespective of polytype and conduction type. In n-type samples, the latter process is dominated by two different types of defects. In n-type 6H SiC, $Z_{1/2}$ levels emerged after annealing at 800°C. The $Z_{1/2}$ levels disappeared around 1100°C with an appearance of $E_{1/2}$ levels. The $E_{1/2}$ levels are eventually annealed at 1500–1700°C. Similar annealing behavior was observed for the corresponding levels in n-type 4H SiC, i.e., $RD_{1/2}$ and $Z_{1/2}$ levels. The overall annealing behavior of vacancy-type defects by positron annihilation and the deep levels are in good agreement above 800°C suggesting that the above deep levels are related to the vacancy-type defects.

*Keywords:* SiC; Positron annihilation; DLTS; Vacancies

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## 1. Introduction

Ion-implantation is an indispensable technique for the selective doping of SiC because of the extremely small diffusion constants of the dopant impurities. Residual defects induced by post-implantation annealing prevent the full activation of dopant impurities. After ion bombardment a series of deep levels have so far been observed in SiC [1]. In particular, two major peaks termed $E_{1/2}$ and $Z_{1/2}$ in 6H SiC and $Z_{1/2}$ and $RD_{1/2}$ in 4H SiC are important after a high temperature annealing above 1000°C [2]. These levels are thought to have the following correspondence: $E_{1/2}:6\text{H}\leftrightarrow Z_{1/2}:4\text{H}$ and $Z_{1/2}:6\text{H}\leftrightarrow RD_{1/2}:4\text{H}$ [1]. That is, the corresponding defects in these polytypes have the same atomic structures. Their origins are still unknown.

In this work, we investigated the annealing processes of vacancy-type defects in 4H and 6H SiC epilayers after He-implantation using positron annihilation spectroscopy (PAS). Deep level transient spectroscopy (DLTS) measurements have also been carried out on the same wafers [3]. From the correlation between PAS and DLTS data, we confirmed that $E_{1/2}$ and $Z_{1/2}$ levels in 6H SiC and $Z_{1/2}$ and $RD_{1/2}$ levels in 4H SiC are originating from vacancy-type defects.

## 2. Experimental

Samples were cut from chemical vapor deposition (CVD) grown 4H and 6H SiC films doped with nitrogen (n-type) or aluminum (p-type) with approximately 5 μm thick on the respective substrates. The net doping concentration was approximately $5\times10^{15}\,\text{cm}^{-3}$. In order to generate a box-shape defect profile in the epilayers, the samples were implanted with He ions at

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energies (doses) of 30 keV ($8 \times 10^{11}\,\text{cm}^{-2}$), 100 keV ($9.5 \times 10^{11}\,\text{cm}^{-2}$), 210 keV ($9.5 \times 10^{11}\,\text{cm}^{-2}$), 350 keV ($9.5 \times 10^{11}\,\text{cm}^{-2}$), 500 keV ($9.5 \times 10^{11}\,\text{cm}^{-2}$), 650 keV ($1 \times 10^{12}\,\text{cm}^{-2}$), 800 keV ($1.1 \times 10^{12}\,\text{cm}^{-2}$) and 950 keV ($1.3 \times 10^{12}\,\text{cm}^{-2}$) at room temperature. Isochronal annealing was conducted from 100°C to 1700°C for 30 min in vacuum or dry argon ambient. Positron annihilation Doppler broadening measurements were performed with the positron beam at an incident energy ($E$) below 40 keV. The energy windows for the peak intensity ($S$-parameter) and tail intensity ($W$-parameter) are 511.0 + 0.9 and 516.0 + 6.0 keV, respectively. Positron lifetime measurements were also carried out with a pulsed beam at $E = 17$ keV. The time resolution of the spectrometer was approximately 260 ps. All the unimplanted samples showed a unique $S$-parameter at $E > 15$ keV. Only one lifetime component (140–145 ps), which agreed with the SiC bulk lifetime [4], was found in unimplanted p-type samples though the spectra of unimplanted n-type samples that were strongly modulated due to the positron reemission effect. Thus, we use unimplanted p-type samples as references and suppose that $S$-parameter at $E > 15$ keV represents the bulk value.

## 3. Results and discussion

Fig. 1 shows the positron lifetime spectra for He-implanted samples with a reference sample (unimplanted p-type 6H). The positron lifetime shows a similar increase after implantation in both polytypes and conduction types. The average lifetime after implantation is determined to be approximately 210 ps for all the samples. Two-component analyses gave rise to the defect-related lifetime ($\tau_2$) of $236 \pm 8$ ps with an intensity of 60–70%. Fig. 2 shows $S$-parameter after implantation (normalized to the bulk $S$-parameter) with that of the reference sample as a function of incident positron energy. After implantation, $S$-parameter increases homogeneously from the unimplanted level at $3\,\text{keV} < E < 17\,\text{keV}$ and approaches the bulk value with increasing energy. This indicates that vacancies are homogeneously distributed in the implanted region. The depth profiles of vacancies determined by the VEPFIT program considering the one-dimensional diffusion of positrons [5] actually agreed with that calculated from SRIM simulation [6]. The average $S$-parameter in the implanted region is 1.056. There are no significant differences between different polytypes and conduction types in both lifetime spectra and $S-E$ relations. The absence of polytype dependence on $S$-parameter and lifetime shows that the same types of vacancies are generated as positron trapping centers irrespective of the polytype. The absence of conduction type dependence can be explained as the shift of the Fermi level towards the mid-gap in both n- and p-type samples so that positron-trapping centers are retained in the same charge states. The observed $S$-parameter ($\sim 1.06$) and positron lifetime ($\tau_2 = 236$ ps) in the damage region greatly exceed the specific values for isolated silicon vacancies (1.028–1.031 [7] and $\sim 190$ ps [8], respectively). This shows that both single vacancies and further vacancy agglomerates, such as divacancies, are

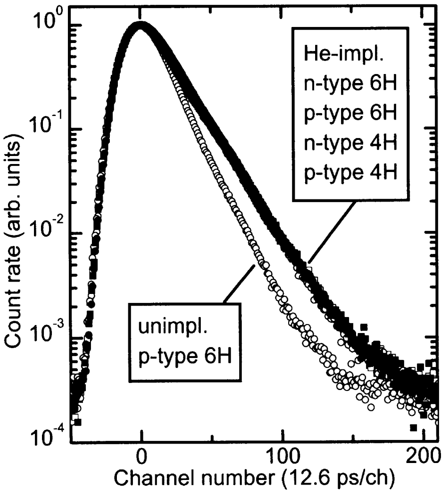

Fig. 1. Positron lifetime spectra of an unimplanted p-type 6H SiC (as a reference) and of He-implanted samples.

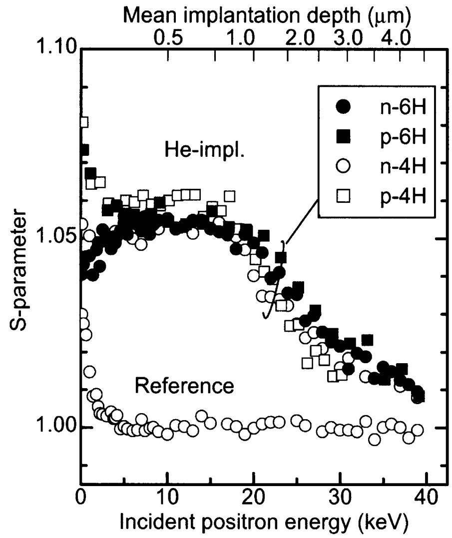

Fig. 2. $S$-parameter for the reference sample (unimplanted p-type 6H SiC) and for the He-implanted samples as a function of incident positron energy. The $S$-parameter is normalized to that of the reference sample at $E > 15$ keV.

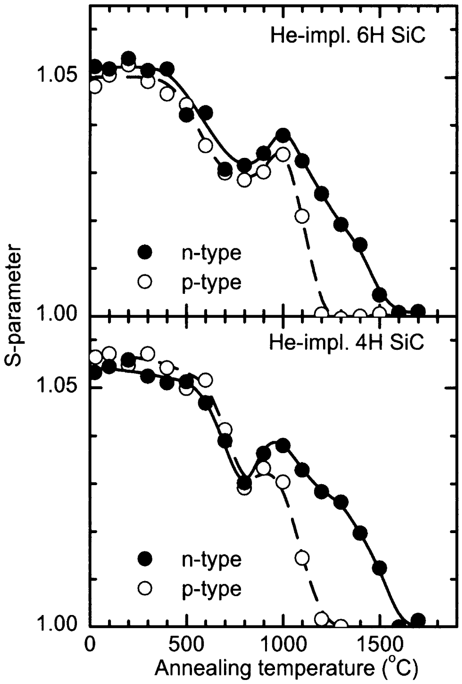

Fig. 3. $S$-parameter for He-implanted samples as a function of annealing temperature.

generated by implantation. This is naturally understood in terms of nuclear collisions near the ranges of He ions.

Fig. 3 shows the annealing behavior of the $S$-parameter in the damage region determined by the VEPFIT analysis. The annealing behaviors for 4H and 6H samples are quite identical. This again shows that the similar damages are created in both polytypes. One may divide the annealing process of $S$-parameter into three parts: (i) the first decrease at 500–700°C; (ii) a slight increase around 1000°C and (iii) a final recovery above 1100°C. In the first part, the defect-related positron lifetime was similar to that for the as-implanted sample ($\tau_2 = 236\,\text{ps}$), while the intensity decreased from approximately 70% to 50%. The first annealing process is primarily interpreted as the disappearance of as the single vacancies. This is in good agreement with the previous report that isolated silicon and carbon vacancies are mobile below 1000°C [9]. The increase of the $S$-parameter in the second part implies the generation of complex defects. Probably, a part of mobile vacancies agglomerates or combines with other defects. The former two processes are commonly observed for both conduction types suggesting a lesser influence of dopant impurities. The $S$-parameter for the p-type samples decreases steeply around 1100°C and reaches the unimplanted level already at 1200°C. Contrary to this steep recovery for the p-type samples, the n–type samples show a somewhat broad feature. This means that another type of defects, which cannot be seen in p-type samples, is detected in n-type samples above 1200°C. There are two possible ways to explain this result: (i) Only one type of defect exists in p-type samples, while two types of defects (one of them is common to p-type) exist in n-type, or (ii) Two types of defects acting as positron trapping centers exist in both n- and p-type samples. One of them, which has a higher thermal stability, is not detected in p-type samples due to the recovery of the Fermi level accompanying the disappearance of the majority of defects so as to charge positron-trapping centers more negatively and positively in n- and p-type samples, respectively. It is rather difficult to decide which of the above possibilities actually occur. However, in any case, two different types of defects contribute to the annealing process of n-type samples above 1000°C. The increase of $S$-parameter at 1000°C was not observed in the case of electron-irradiated samples [10]. It is assumed that He-implantation causes much more complicated damage structures than electron irradiation. Therefore, we suppose that such an effect preferentially appears with higher amount of damages. The final recovery of $S$-parameter above 1200°C for n-type samples is also observed in the electron-irradiated samples. Thus, the same type of defects should be responsible for this annealing process in He-implanted and electron-irradiated samples. From the detailed analyses of the electron-irradiated samples, we proposed that complex defects related to silicon vacancies are important. It is interesting to note that even in the case of He-implantation, which may resulting in a heavier damage than electron irradiation, all the vacancy-type defects detected by positron annihilation vanish after annealing at 1700°C as well as in electron irradiation case.

We compare the above-described positron annihilation and DLTS experiments. After annealing above 700°C, $E_{1/2}$ and $Z_{1/2}$ levels in 6H and $Z_{1/2}$ and $RD_{1/2}$ levels in 4H are observed [3]. The concentrations of these levels are determined by $C-V$ characteristics. Fig. 4 shows the annealing behavior of these levels with the respective $S$-parameters. The concentrations of $Z_{1/2}$ in 6H and $RD_{1/2}$ in 4H samples slightly increase at 1000°C and drastically decrease until 1200°C. The concentrations of $E_{1/2}$ in 6H and $Z_{1/2}$ in 4H increase from 1000°C along with the decreases of $Z_{1/2}$ in 6H and $RD_{1/2}$ in 4H and finally decrease above 1400°C. One can immediately find that these successive annealing behaviors of $E_{1/2}$ and $Z_{1/2}$ levels in 6H and $Z_{1/2}$ and $RD_{1/2}$ levels in 4H are in good agreement with what we observed for the $S$-parameter. That is, increase in the concentrations of $Z_{1/2}$ in 6H and $RD_{1/2}$ levels in 4H closely matches with that of $S$-parameter at 1000°C. The decrease in the concentrations of $E_{1/2}$ in 6H and $Z_{1/2}$ levels in 4H coincides with the final recovery of $S$-parameter at

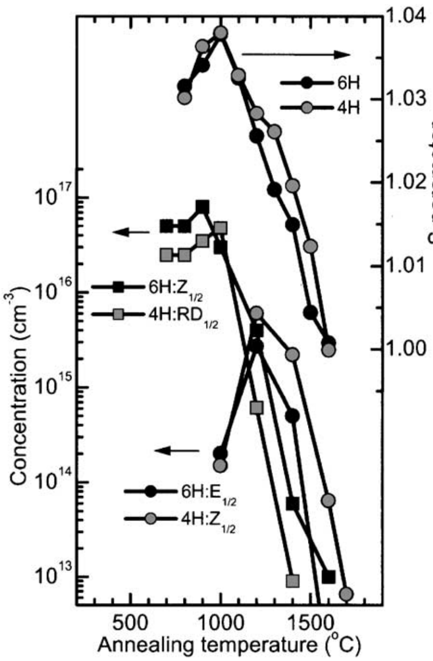

Fig. 4. Annealing behavior of the *S*-parameter and concentrations of the observed deep levels ($E_{1/2}$ and $Z_{1/2}$ levels in 6H and $Z_{1/2}$ and $RD_{1/2}$ levels in 4H SiC) for He-implanted samples in the annealing temperature range above 800°C.

1200°C. Thus, the above electronic levels should be related to vacancy-type defects detected by positron annihilation. Recently, we also proposed that $E_{1/2}$ in 6H and $Z_{1/2}$ in 4H should be silicon-vacancy-related defects using electron-irradiated epilayers [10]. This proposal is again supported here.

## 4. Summary

In summary, we investigated the annealing process of vacancy-type defects in 4H and 6H SiC CVD epilayers after He-implantation. There are no essential differences between 4H and 6H samples in their annealing process. From the comparison between n- and p-type samples, it was found that two types of vacancies contribute to the annealing process above 1000°C in n-type samples. The overall annealing behavior for vacancy-type defects agrees with the successive annealing of $Z_{1/2}$ and $E_{1/2}$ levels in 6H and $Z_{1/2}$ and $RD_{1/2}$ levels in 4H SiC.

## Acknowledgements

One of the author (A.K.) thanks the Alexander von Humboldt Stiftung for their financial support to promote this research project.

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