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Positron lifetime studies on 8 MeV electron-irradiated n-type 6H silicon carbide

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Abstract

The positron lifetime technique was employed to study vacancy-type defects in 8 MeV electron-irradiated n-type 6H silicon carbide. A long-lifetime component having a characteristic lifetime of 223–232 ps was observed in the irradiated sample and was attributed to the V_CV_{Si} divacancy. Other positron traps, which dominated at low temperatures, were observed to compete with the V_CV_{Si} for trapping positrons. A positron trapping model involving a positron shallow trap, a negatively charged monovacancy and the V_CV_{Si} divacancy was found to give a good description of the temperature-dependent positron lifetime data of the 1200 °C annealed sample. The identity of the monovacancy could not be unambiguously determined, but its lifetime was found to be in the range 160–172 ps.

1. Introduction

Silicon carbide is a wide band gap semiconductor suitable for fabricating high temperature, high power, high frequency and radiation-resistant devices [1]. As many defects determine the electrical and optical properties of the host material, knowledge about these defects is most important for device fabrication. Despite the extensive effort made hitherto to understand the defects in 6H-SiC, the knowledge available is far from complete. Having the advantage of being selectively sensitive to vacancy-type defects and the capability to yield extensive information such as concentration, charge state, ionization energy and microstructure, positron annihilation spectroscopy has been extensively used to study vacancy-type defects in different semiconductors such as Si and GaAs [2, 3]. Acting as a potential well for the diffusing

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Table 1. Summary of characteristic positron lifetimes of bulk 6H-SiC, the carbon vacancy-related defect, the silicon vacancy-related defect and the V_CV_{Si} divacancy.

	Lifetime (ps)		Reference
Bulk	141	First-principles calculation	[4]
	144	As-grown n- and p-type, 10 MeV e^- irradiated p-type. Defect components exist and τ_b calculated from the model	[9]
	136	As-grown and e^- irradiated p-type, single component	[14]
	148	Defect component exists, calculated from the model	[6]
	142	As-grown n-type; single component	[15]
	146	As-grown n-type	[10]
	145	As-grown p-type	[13]
V_C-related	153	First-principle calculation	[4]
	160	2.2 and 10 MeV e^- irradiated n-type	[9]
	153	0.3 MeV e^- irradiated n-type	[10]
	152	2.2 MeV e^- irradiated n-type; annealed at 77–177 °C	[11]
	175	Formed above 1243 °C, persisted up to 1743 °C	[11]
V_{Si}-related	194	First-principles calculation	[4]
	260	2.2 and 10 MeV e^- irradiated n-type	[9]
	189	3 MeV e^- irradiated n-type. Isolated V_{Si} annealed at 750 °C	[14]
	183	3 MeV e^- irradiated n-type. V_{Si}–N complex annealed at 1400 °C	[14]
	175	2.2 MeV e^- irradiated n-type; V_{Si} Frenkel pair annealed at 697–927 °C	[11]
	200	10 MeV e^- irradiated n-type; isolated V_{Si}	[11]
	176	0.5 MeV e^- irradiated n-type	[10]
	202	12 MeV proton irradiated n-type	[8]
	210	2 MeV e^- irradiated n-type	[13]
V_CV_{Si}	214	First-principles calculation	[4]
	225	12 MeV proton irradiated n-type	[8]
	234	Ge-implanted	[7]
	232	Non-irradiated n-type	[6]

positron, the neutral or negatively charged vacancy-type defects may trap the positron, which will finally annihilate in this localized defect state rather than in the delocalized Bloch state. The information about the electronic environment in which the positron annihilates can be revealed by the outgoing annihilation gamma photons. Vacancy-type defects in 6H-SiC have previously been studied by the positron lifetime technique, and the results are summarized in table 1.

Theoretical studies of these defects showed that the 6H-SiC bulk, the carbon vacancy, the silicon vacancy and the V_CV_{Si} divacancy to have lifetimes of 141, 153, 194 and 214 ps, respectively [4]. For experimental works, the characteristic lifetimes of the V_CV_{Si} divacancy reported from different research groups agreed quite well and were within the range of 225–232 ps [5–8]. For the C-vacancy-related defect, the lifetime of the isolated V_C was in the range of 152–160 ps [9–11]. Dannefaer and Kerr [11] have assigned the 175 ps component to the V_CV_{Si} complex. In the case of the Si-vacancy-related defect, the reported positron lifetime values were diverse, ranging from 175 to 260 ps [8–14]. As for the bulk lifetime, values of 136–148 ps have been reported [6, 8, 9, 13–15].

In the present study, positron lifetime spectroscopy was employed to study the vacancy-type defects in 8 MeV electron-irradiated n-type 6H-SiC samples. The positron lifetime spectra were decomposed into individual components and models were constructed to describe the temperature dependence of the positron trapping parameters.

2. Experimental details

The samples used in the present study were cut from a nitrogen-doped Lely grown 6H-SiC wafer ($n \sim 1.2 \times 10^{18}$ cm^{-3}) purchased from Cree Research Inc. They were irradiated by electrons of energy 8 MeV and dosage of 1×10^{17} cm^{-2}, the temperature being maintained at <60 °C during the irradiation process. The positron source was 30 μCi of ^{22}Na radioisotope encapsulated with two kapton foils. The source was then sandwiched with two pieces of the samples being investigated. Temperature-dependent positron lifetime measurements were performed with the sample ensemble mounted in an Oxford 10K closed cycle He fridge. The positron lifetime spectrometer was a fast–fast coincident system having a resolution of FWHM = 230 ps. Each spectrum contained four million annihilation events. All the annealing steps were performed in forming gas ($N_2 : H_2$, 80% : 20%) for a period of 30 min. Taking into account the instrumental resolution, background contribution and source correction, the lifetime spectra were analysed using the program POSITRONFIT [16], which fits the spectra with the expression $\sum I_i \exp(-t/\tau_i)$, where τ_i and I_i are the characteristic lifetime and the intensity of the lifetime component, respectively.

3. Results and discussion

Room temperature positron lifetime measurements were performed on electron-irradiated samples annealed at different temperatures, and the resulting average lifetime, defined as $\tau_{\text{ave}} = \sum_i I_i \tau_i$, is shown in figure 1(a). The average lifetime of the as-grown control sample was 161 ps. The increase in the average lifetime from 161 to 190 ps after electron irradiation implies the introduction of positron trapping vacancies by the irradiation process because positron annihilating at a defect state usually has a lifetime longer than that at the delocalized bulk state. The average lifetime decreases from ~190 to 178 ps as the annealing temperature increases to 200 °C and then slowly decreases to ~170 ps as the annealing temperature further reaches 1200 °C. All the spectra of the as-irradiated sample annealed at different temperatures were well fitted by the two-component model but not by the single-component model. The fitting parameters $\tau_{1,\text{exp}}$, $\tau_{2,\text{exp}}$ and $I_{2,\text{exp}}$ are shown in figures 1(b)–(d), respectively. From figure 1(c), the characteristic lifetime of the long lifetime component $\tau_{2,\text{exp}}$ was found to be independent of the annealing temperature and had a value of 228 ± 1 ps. It is also noticed that the intensity of this long-lifetime component decreases from 54 to 38% as the annealing temperature reaches 200 °C and then persists up to 1200 °C.

Lifetime spectra of the 1200 °C annealed electron-irradiated sample taken at temperatures ranging from 25 to 294 K were well represented by two components, and the long-lifetime component was found to have a constant value of 232 ± 4 ps independent of measurement temperature. The fitted values of $\tau_{1,\text{exp}}$, $I_{2,\text{exp}}$ and the average lifetime as a function of temperature are shown in figure 2. The observation from figure 2 that the average lifetime and fitted $I_{2,\text{exp}}$ increase with temperature imply that more positrons annihilate in the long-lifetime component at high measurement temperatures. In order to check the validity of the simple trapping model, we have calculated the modelled bulk lifetime by the following equation [2]: $\tau_{b,\text{mod}} = (I_1\lambda_1 + I_2\lambda_2)^{-1}$, where $\tau_i = 1/\lambda_i$ are the fitted lifetimes. The calculated $\tau_{b,\text{mod}}$ is shown in figure 2(a) and it is not consistent with physical reality because: (i) it has no significant change at 100–300 K and then decreases rapidly from ~166 to ~160 ps as the temperature

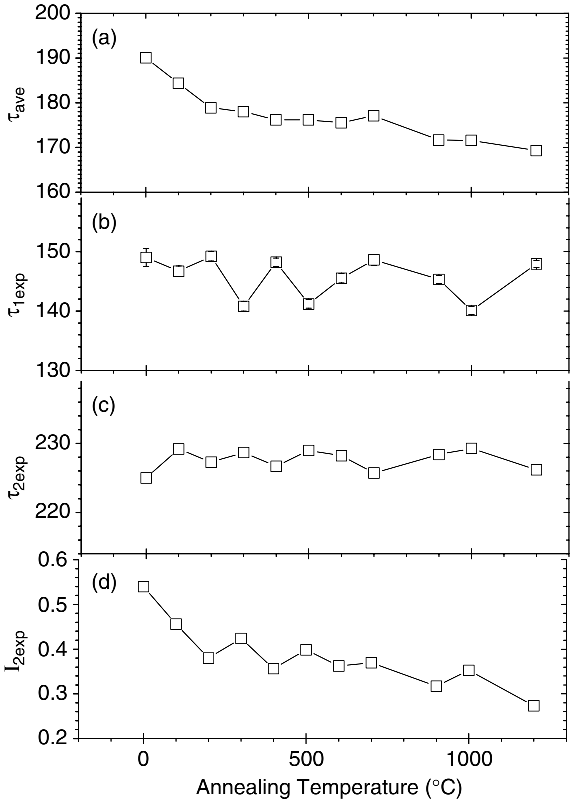

Figure 1. (a) Average positron lifetime, (b) the fitted $\tau_{1,\mathrm{exp}}$, (c) the fitted $\tau_{2,\mathrm{exp}}$ and (d) the fitted $I_{2,\mathrm{exp}}$ as a function of the annealing temperature for the as-irradiated n-type 6H-SiC sample irradiated by electrons with energy of 8 MeV and dosage of 1.2×10^{18} cm^{-2}.

decreases from 100 to 25 K, whereas the bulk positron lifetime should slightly decrease with decrease in temperature and (ii) the calculated $\tau_{b,\mathrm{mod}}$ is much larger than the previously reported 6H-SiC bulk lifetime (~145 ps). This implies that positron trapping centres other than the long-lifetime component exist in the present 1200 °C annealed irradiated sample.

Our findings showed that the two-component model is a good representation for all the lifetime spectra of the electron-irradiated sample, and the long-lifetimes were found to be constant at ~230 ps irrespective of the annealing or measurement temperature. With first-principles calculation, Brauer *et al* [4] have reported the lifetime values of the 6H-SiC bulk, the carbon vacancy, the silicon vacancy and the V_CV_{Si} divacancy to be 141, 153, 194 and 214 ps, respectively. For experimental works, the lifetime of the V_CV_{Si} divacancy was reported to be 225–234 ps (see table 1). The present observed lifetime component (~230 ps) is in good agreement with these previously observed values and this component is thus attributed to the V_CV_{Si} divacancy.

Polity *et al* [15] have studied the electron irradiated 6H-SiC materials with the positron lifetime technique. A two-component model ($\tau_{1,\mathrm{exp}} = 178$ ps and $\tau_{2,\mathrm{exp}} = 222$ ps) was found to give a good representation for the spectrum of the as-irradiated sample taken at 90 K. The $\tau_{1,\mathrm{exp}}$ is possibly the combined lifetime component of the trapping model τ_1 and the Si vacancy ($\tau[V_{Si}] \sim 183$–194 ps). In our previous positron lifetime study of non-irradiated

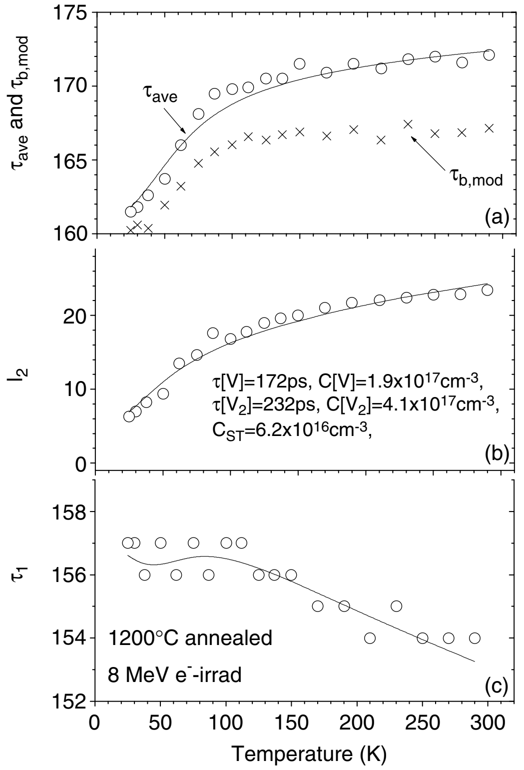

Figure 2. (a) Average positron lifetime, (b) the fitted I_2 and (c) the fitted τ_1 as a function of the measurement temperature for the 1200 °C annealed electron-irradiated n-type 6H-SiC sample. The bulk lifetime (×) shown in (a) was calculated by the simple trapping model as described in the text. The solid curves were calculated by the model involving the monovacancy, V_CV_{Si} and the positron shallow trap as described in the text.

6H-SiC annealed at different temperatures [6], the two-component model was found to give a satisfactory fit to the spectra. The long-lifetime was found to be about 200 ps for the as-grown sample. It increased with increase in annealing temperature and then saturated at about 230 ps after the ~700 °C annealing. This lifetime component was attributed to the merging of components of the V_{Si} and V_CV_{Si} defects (having lifetimes of ~190 and 230 ps, respectively) and the increase in the lifetime was due to the annealing of the Si vacancy [6]. The annealing out of the Si vacancy at about 700 °C also agreed well with the results of the electron paramagnetic resonance (EPR) and photoluminescence studies [17, 18]. This indicates that, for the present study, absence of the C- or Si-vacancy positron lifetime components in the spectra does not simply imply that these two defects are absent in the samples. It is because these components, if they exist, may merge into the τ_1 or the V_CV_{Si} component if their lifetimes are too close to be separable. For the present study, the long-lifetime component has a constant value of 228–232 ps irrespective of the annealing or measurement temperature. Moreover, this characteristic lifetime coincides well with the generally accepted lifetime value of V_CV_{Si}. There was thus no sign of such merging of the V_{Si} (or the V_C) component with the V_CV_{Si} component. However, we cannot exclude the possibility of merging of the V_C or the V_{Si} component with the τ_1 component. Nevertheless, it is reasonable to conclude that the long-lifetime component observed in the present study originates from the V_CV_{Si} defect.

In figure 2, it is clearly shown that the average lifetime and the long-lifetime component intensity increase with temperature, and this implies that more positrons annihilate in the $V_C V_{Si}$ state at higher temperatures. Similar observations were also reported in the non-irradiated n-type 6H-SiC sample [5, 6]. The increase of average lifetime and I_2 as a function of temperature were explained by the presence of a positron trap competing with the long-lifetime defect in trapping positrons. The positron trapping rate of this trap increased with decrease in temperature and its characteristic lifetime was smaller than that of the long-lifetime component. This would lead to the result that τ_{ave} and I_2 increase with increase in temperature. In the same paper, it was shown that the lifetime data could possibly be well fitted by two different models, namely the positron shallow trap and the negatively charged carbon vacancy. It was shown that, from the lifetime data alone, it was impossible to distinguish which model was the low-temperature positron trap.

A positron shallow trap is a hydrogen-like system in which the positron is bound to an ionized acceptor [19, 20]. It has a binding energy of ~10–100 MeV. This implies that positron detrapping from the shallow trap is significant at high temperatures and it plays an important role only at low temperatures. Moreover, as the positron bound in the shallow trap is loosely bound, it experiences an electronic environment very similar to that of the delocalized positron. This implies that the positron shallow trap would have a non-distinguishable characteristic lifetime from that of the bulk state. Details of a trapping model containing a shallow trap and a long-lifetime non-detrapping defect can be found in [2]. The main difference between the present data (i.e. for the 1200 °C annealed 8 MeV electron-irradiated sample) shown in figure 2 and the data in [5, 6] (i.e. for the non-irradiated sample) is that the fitted τ_1 of the irradiated sample has values significantly larger (varying from 154 to 157 ps see the data in figure 2) compared with that of the non-irradiated sample (varying from 127 to 142 ps in [5, 6]). We have attempted to fit the experimental data as shown in figure 2 with a model consisting of the $V_C V_{Si}$ divacancy and the positron shallow trap, but we could not obtain a reasonably good fit to the data with parameters compatible with physical reality.

For the negatively charged vacancy, its specific positron trapping coefficient follows the temperature dependence of $\mu \sim T^{-0.5}$ [21]. The rate of positrons being trapped by such a defect is equal to $\kappa = \mu C$, where C is the vacancy concentration [2, 3]. As the temperature increases, the positron trapping rate into such a defect would decrease. This implies that, other than the $V_C V_{Si}$ divacancy, if there exists a negatively charged monovacancy (i.e. V_C or V_{Si}) that has a lifetime less than $\tau_{V_C\,V_{Si}}$ and inseparable from the τ_1 component, the expected lifetime spectra would behave similar to the present observation (i.e. $\tau_2 =$ constant and τ_{ave} and I_2 increase with temperature). The rate equations describing positrons trapping, annihilating from and detrapping from (only for the case of the shallow trap) the bulk state, the two vacancy-type defect states and the positron shallow trap state are given by [2]:

$$
\begin{aligned}
\frac{\mathrm{d}n_b}{\mathrm{d}t} &= -(\lambda_b + \kappa_V + \kappa_{V_2} + \kappa_{ST})n_b(t) + \delta n_{ST}(t),\\
\frac{\mathrm{d}n_{V_{ST}}}{\mathrm{d}t} &= -(\lambda_{ST} + \delta)n_{ST}(t) + \kappa_{ST}n_b(t),\\
\frac{\mathrm{d}n_V}{\mathrm{d}t} &= -\lambda_V n_V(t) + \kappa_V n_b(t),\\
\frac{\mathrm{d}n_{V_C V_{Si}}}{\mathrm{d}t} &= -\lambda_{V_2} n_{V_2}(t) + \kappa_{V_2} n_b(t).
\end{aligned}
\qquad (1)
$$

$n_i(t)$ is the normalized positron density in state i at time t, and subscripts b, ST, V and V_2 represent the bulk, shallow trap, competing monovacancy and divacancy, respectively. λ_i and κ_i are the annihilation rate of and the trapping rate into the state i. Thus the modelled lifetime spectrum (i.e. $\sum I_i \exp(-t/\tau_i)$) could be obtained by solving these equations and it was found to contain four components with [2]:

$$
\begin{aligned}
&\tau_1 = 2/(X+Y), \qquad \tau_2 = 2/(X-Y), \qquad \tau_3 = 1/\lambda_V, \qquad \tau_4 = 1/\lambda_{V_2},\\
&I_1 = 1-(I_2+I_3+I_4),\\
&I_2 = \frac{\delta+\lambda_{ST}-\frac{1}{2}(X-Y)}{Y}\\
&\qquad \times\left\{1+\frac{\kappa_{ST}}{\delta+\lambda_{ST}-\frac{1}{2}(X-Y)}+\frac{\kappa_V}{\lambda_V-\frac{1}{2}(X-Y)}+\frac{\kappa_{V_2}}{\lambda_{V_2}-\frac{1}{2}(X-Y)}\right\}, \qquad (2)\\
&I_3 = \frac{\kappa_V(\delta+\lambda_{ST}-\lambda_V)}{\left\{\lambda_V-\frac{1}{2}(X+Y)\right\}\left\{\lambda_V-\frac{1}{2}(X-Y)\right\}},\\
&I_4 = \frac{\kappa_{V_C V_{Si}}(\delta+\lambda_{ST}-\lambda_{V_2})}{\left\{\lambda_{V_2}-\frac{1}{2}(X+Y)\right\}\left\{\lambda_{V_2}-\frac{1}{2}(X-Y)\right\}},
\end{aligned}
$$

where X and Y are given by [2]:

$$
\begin{aligned}
X &= \lambda_b+\kappa_{ST}+\kappa_V+\kappa_{V_2}+\lambda_{ST}+\delta,\\
Y &= \{(\lambda_b+\kappa_{ST}+\kappa_V+\kappa_{V_2}-\lambda_{ST}-\delta)^2+4\delta\kappa_{ST}\}^{1/2}.
\end{aligned}
\tag{3}
$$

The two shallow-trap-related components (i.e. τ_1 and τ_2 in equation (1)) and the V_C component are inseparable. They thus merge to form the first experimental component of the lifetime spectrum $\tau_{1,\mathrm{exp}}$ and thus [2]:

$$
\begin{aligned}
&\tau_{1,\mathrm{exp}} = \sum_{i=1}^{3}\frac{I_i}{I_1+I_2+I_3}\tau_i, \qquad \tau_{2,\mathrm{exp}} = \frac{1}{\lambda_{V_2}},\\
&I_{2,\mathrm{exp}} = I_4, \qquad I_{1,\mathrm{exp}} = 1-I_{2,\mathrm{exp}}.
\end{aligned}
\tag{4}
$$

The detrapping rate from the shallow trap is given by [22]:

$$
\delta_{ST} = \frac{\kappa_{ST}}{C_{ST}}\left(\frac{m_{e^+}}{2\pi\hbar^2}\right)^{3/2}(kT)^{3/2}\exp\left(-\frac{E_b}{kT}\right), \tag{5}
$$

where m_{e^+} is the positron effective mass and E_b is the binding energy of the positron shallow trap.

We have attempted to fit the positron lifetime data of the 1200 °C annealed electron-irradiated sample (figure 2) with this model. In the fitting, values of $\mu_{ST} = 5\times10^{16}\ \mathrm{s^{-1}}$, $\tau_{V_2} = \tau_{V_C V_{Si}} = 232$ ps, $\mu_{V_C V_{Si}} = 8\times10^{14}\ \mathrm{s^{-1}}$ and μ_V (300 K) $= 3.8\times10^{15}\ \mathrm{s^{-1}}$ were fixed [5, 6]. However, it was difficult to obtain definitive values for the other parameters in the fitting process because, for some of the parameters (such as τ_V and C_V), good fits to the data exist in quite a wide range of these parameters. Simultaneous good fits to τ_{ave}, $\tau_{1,\mathrm{exp}}$ and $I_{2,\mathrm{exp}}$ were obtained with the parameters falling in the ranges $E_b =$ 10–13 MeV, $C_{ST} = 5\times10^{16}\ \mathrm{cm^{-3}}$, $\tau_b =$ 145–148 ps, $\tau_V =$ 160–172 ps, $C_V = 1.9$–$4.2\times10^{17}\ \mathrm{cm^{-3}}$ and $C(\mathrm{V_C V_{Si}}) = 4\times10^{17}\ \mathrm{cm^{-3}}$. One of the typical well-fitting curves is also shown in figure 2. The fitted lifetime range of the monovacancy (i.e. 160–172 ps), which corresponds to $\tau_d : \tau_b =$ 1.09–1.19, also falls within the expected range of the defect lifetime to bulk lifetime ratio. Nevertheless, this result implies that, after the 1200 °C annealing, other than the V_CV_{Si} divacancy, a monovacancy having lifetime in the range 160–172 ps existed in the sample.

Monovacancy-type defects in 6H-SiC have previously been investigated by a non-positron-annihilation technique such as electron spin resonance (ESR). There are many ESR studies showing that the carbon vacancy-related defects are thermally stable up to 1200 °C. In electron- and neutron-irradiated 6H-SiC, Balona and Loubser [23] detected the carbon vacancy-related ESR signals that annealed at 1400 °C. EI5 and EI6 are the two EPR signals thermally survived up to 1600 °C annealing and their structures are suggested to be related to carbon vacancy [24–26]. The EPR signal attributed to V_CC_{Si} (P6/P7) was identified in 600, 1000 and 1200 °C annealed neutron-irradiated n-type SiC and it was suggested to be the product of the annealing of the Si vacancy. For the case of silicon vacancy-related defects, most of the results showed that the isolated Si vacancy annealed at temperatures below 1000 °C. In the studies of Sörman *et al* [17] and Wagner *et al* [27], the V_1, V_2 and V_3 photoluminescence signals were attributed to the isolated Si vacancy, and this defect disappeared after the 750 °C annealing. Using ESR, magnetic circular dichroism of absorption (MCDA) and MCDA-detected EPR, Linger *et al* [18] observed annealing of the Si vacancy between 600 and 1000 °C and the V_CC_{Si} defect was suggested to be the annealing product.

Positron lifetime measurements have been extensively carried out to investigate the vacancy-type defects in silicon carbide materials [4–15]. It is generally accepted that the V_CV_{Si} defect has a relatively long-lifetime of 225–232 ps [6–8]. For the case of carbon vacancy-related defects, most of the reported characteristic lifetime values (152–160 ps) [4, 9–11] are relatively close to the 6H-SiC bulk lifetime (136–146 ps) [4, 6, 9, 10, 13–15], despite the report of the 175 ps component found in the 1243 °C annealed electron-irradiated sample, which was ascribed to the V_CC_{Si} [11]. However, diverged values of characteristic positron lifetime were reported for the silicon vacancy (175–210 ps) [4, 8, 10, 11, 14]. There are possibly two explanations for this divergence. One explanation is that different characteristic positron lifetimes are due to different silicon vacancy defect complexes found in samples irradiated with electrons and annealed under different conditions. Another explanation is that the fitted long-lifetime component is indeed the combined result of more than one positron trap (possibly the silicon vacancy and the V_CV_{Si} divacancy) with their lifetimes too close to be separated. The characteristic lifetime values of isolated V_{Si} have been suggested to be 189, 194 and 200 ps and there are results of positron lifetime and ESR studies reporting its annealing after the ∼750 °C annealing [6, 14, 18]. The V_{Si} Frenkel pair was reported to have a lifetime of 175 ps and it annealed between 697 and 927 °C [11]. The V_{Si}–N complex was found to have a lifetime of 183 ps and anneal at 1400 °C [14]. The monovacancy observed in the present 1200 °C annealed electron-irradiated sample is thus not related to the isolated V_{Si} and V_{Si} Frenkel pair, as these two defects anneal at relatively low temperatures. A lifetime value of 183 ps for the thermally stable V_{Si}–N complex is not in the fitted lifetime range of the present monovacancy (160–172 ps), although we cannot rule out the possibility of its contribution to the present monovacancy lifetime. Nevertheless, the 160–172 ps monovacancy observed in the present 1200 °C annealed electron irradiated sample must contain the carbon vacancy-related defect having the reported lifetimes of 152–175 ps [4, 9–11]. The 1200 °C thermally stable V_C-related defect also agrees well with the results of previous ESR studies.

It would be interesting to compare the results of the present 8 MeV electron-irradiated 6H-SiC sample with those of the non-irradiated 6H-SiC sample cut from the same wafer that was previously reported in [6]. The average lifetime of the as-grown sample is 161 ps, which is much smaller when compared with the as-irradiated sample (i.e. 190 ps). However, the value of 161 ps is much larger than the bulk lifetime of 6H-SiC and thus a significant amount of vacancy-type defects exists in the as-grown sample. The positron lifetime spectrum of the

Table 2. Comparison of the fitted parameters of electron-irradiated 6H-SiC samples from spectra obtained in the present study Polity *et al* [15] with those of Kawasuso *et al* [14].

	Present study (8 MeV, 60 °C and 10^{18} cm^{-2})		Polity *et al* [15] (2 MeV, liquid N_2 temperature and 10^{17} cm^{-2})		Kawasuso *et al* [14] (3 MeV, 60 °C and 10^{17} cm^{-2})	
Parameter	As-irradiated	1200 °C annealed	As-irradiated	1200 °C annealed	As-irradiated	1200 °C annealed
$\tau_{1,\mathrm{exp}}$	155 ps	150 ps	178 ps	145 ps	118 ps	97 ps
$\tau_{2,\mathrm{exp}}$	223 ps	226 ps	222 ps	210 ps	210 ps	183 ps

as-grown sample was found to be well described by the two-component fit with $\tau_2 = 200$ ps. The value of τ_2 increases with increase in annealing and saturates at ~232 ps once the annealing temperature reaches 900 °C. The smaller τ_2 observed at lower annealing temperature has been attributed to the merging of the isolated Si vacancy component (183 ps) and the V_CV_{Si} divacancy component (~230 ps) [6]. The increase in the observed τ_2 was explained by the annealing out of the isolated V_{Si} [6], which has been reported to disappear after the 750 °C annealing [18]. The 232 ps saturated lifetime observed at annealing temperatures higher than 900 °C was thus the pure V_CV_{Si} component. Moreover, a positron trap with lifetime inseparable from τ_1 was revealed by its competition in trapping positrons with the Si vacancy and the divacancy. This defect is possibly an ionized acceptor (i.e. a positron shallow trap) or a carbon vacancy-related defect [6] and it disappears on annealing at 400–650 °C. In the non-irradiated sample annealed at $\leqslant$1200 °C, the concentrations of the C vacancy, Si vacancy and V_CV_{Si} divacancy were lower than 10^{16}, 10^{16} and 10^{17} cm^{-3}, respectively. These values are significantly lower than those obtained in the present 1200 °C annealed 8 MeV electron-irradiated sample ($>10^{17}$ cm^{-3}), which implies that the defects observed in the present study are induced by the electron irradiation.

Polity *et al* [15] (2 MeV, liquid nitrogen temperature and 10^{17} cm^{-2}) and Kawasuso *et al* [14] (3 MeV, 60 °C and 10^{17} cm^{-2}) have also studied the electron-irradiated 6H-SiC sample with the positron lifetime technique. It would be interesting to compare these results with the present study. In all the studies, the lifetime spectra of the as-irradiated samples and the ~1200 °C annealed electron-irradiated samples were well fitted by the two-component model, and some of the fitted parameters are listed in table 2. For the as-grown sample, the present results and Polity *et al*'s results show that τ_2 is about 223 ps and it is attributed to the divacancy. The τ_1 reported are larger than the 6H-SiC bulk lifetime and this implies that this component consists of contributions from the monovacancy V_{Si} and/or V_C. However, the τ_1 of the present sample is lower than that of Polity *et al* [15] (155 and 178 ps, respectively). This possibly implies that the contribution from the Si vacancy to the τ_1 component in our as-irradiated sample spectrum is less than that of Polity *et al* sample spectrum. In Kawasuso *et al*'s analysis [14], the fitted τ_1 is 118 ps and thus there is no sign of monovacancy contribution merging into this component. However, their fitted τ_2 is relatively smaller than the other two and is suggested to be contributed from the silicon vacancy and divacancy [14].

For the 1200 °C samples, as shown in table 2, the fitted τ_2 of the present study and Polity *et al*'s studies are significantly larger than those of Kawasuso *et al*. Kawasuso *et al* have pointed out that the fitted τ_2 decreased from 210 ps (in the as-irradiated sample) to 189 ps together with the corresponding κ_2, which drastically decreases after the ~500 °C annealing. This was attributed to the annealing out of the divacancy and the remaining 189 ps component was related to the isolated Si vacancy. The fitted τ_2 reported by Kawasuso *et al* [14] further reduced to 183 ps above 750 °C and this lifetime was attributed to the V_{Si}–N complex. Kawasuso *et al*'s result that the divacancy anneals at 500 °C is not similar to the finding of the present and Polity *et al*'s studies that the divacancy-related lifetime component persisted at high temperatures such as 1200 °C [6, 15]. Compared with the result of the present study, Kawasuso *et al*'s thermally stable V_{Si}–N component (183 ps) [14] was not found in the present 1200 °C annealed sample because: (i) the monovacancy lifetime of the present 1200 °C annealed irradiated sample is in the range 160–172 ps and (ii) the fitted τ_2 in the present 1200 °C annealed sample is as high as 226 ps, for which merging of the V_{Si}–N complex (183 ps) and the divacancy lifetime components is not likely. It is also noticed that the temperature scan of Polity *et al*'s 1490 K annealed electron-irradiated samples is also not similar to that of the present 1200 °C annealed electron-irradiated sample [15]. All these discrepancies were possibly due to the different composition of defects induced by the different electron irradiation processes with different electron energies and sample temperatures. Moreover, the observed lifetime component could be contributed by more than one vacancy-type defect and this would impose difficulty in accurate interpretation of lifetime data.

4. Conclusion

In conclusion, we have studied the 8 MeV electron-irradiated 6H-SiC samples with the positron lifetime technique. V_CV_{Si} having lifetime of 228–232 ps was identified in the irradiated sample and this defect persisted up to the 1200 °C annealing. In the 1200 °C annealed sample, other positron trapping centres were observed to compete with the V_CV_{Si} divacancy in trapping positrons. These competing traps predominate at low temperatures and possibly originated from the positron shallow trap and the negatively charged monovacancy. The exact identity of the monovacancy is not known, but it is very likely to have some connection with the carbon vacancy defect.

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