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Effects of Illumination on Positron Lifetime of Electron Irradiated n-type 6H-SiC

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Abstract

Positron lifetime experiments under optical illumination have been performed for n-type 6H SiC irradiated with 2 MeV electrons (dose: 1×10^{17} e^-/cm^2). The positron lifetime increases after irradiation indicating the presence of vacancy-type defects. We found that the positron lifetime distinctly decreases upon illumination from that in the darkness below 110K. After the annealing above 1300°C the illumination effect tends to disappear with the disappearance of vacancy-type defects. The illumination effect appeared with a threshold photon energy of 0.47 eV. It was further found that the illumination effect exhibits in a time of 10 min after switching off the light at 15 K.

Introduction

Silicon carbide (SiC) is a key material to produce high power and high frequency electronic devices. Ion implantation is employed for selective doping of SiC. Electron irradiation is also used to control minority carrier lifetime. Therefore, it is important to identify defects induced by irradiation. Former positron lifetime experiments showed that vacancy-type defects induced by electron irradiation ultimately disappear after annealing up to 1500°C [1, 2]. Recent deep level transient spectroscopy (DLTS) studies show the negative-U behavior for E_1/E_2 levels (E_c-0.35-0.40eV) [3, 4]. *Ab initio* calculation also suggests that carbon vacancies exhibit a negative-U character [5]. It is intriguing to clarify the microscopic structures of these energy levels. To clarify if electronic levels observed by DLTS are related to vacancy-type defects, we performed positron lifetime measurements under optical illumination.

Experiment

Samples used in this study are n-type 6H SiC doped with nitrogen ($[N]=1\times10^{17}cm^{-3}$). Electron irradiation was done with 2 MeV electrons up to a dose of 1×10^{17} e^-/cm^2 at room temperature at the Japan Atomic Energy Research Institute. Positron lifetime measurements were performed using a conventional fast-fast positron lifetime spectrometer with ^{22}NaCl (10-90 μCi) in the temperature range from 15 K to 200 K. The measurements under illumination were carried out using an optical cryostat. The effect of illumination on positron lifetime was examined using white and monochromatic light (hν =0.3–3.2 eV). Annealing experiments were done in vacuum from 100°C to 1500°C. Furthermore, to observe the persistency after illumination, we measured positron lifetime in darkness after white light illumination: after illumination for 3 minutes ten spectra were successively measured in ten minutes (i.e., one minute measurements were repeatet tenfold). This sequence was repeated and then each one-minute-spectrum was integrated so that the integrated spectra contain $2x10^6$counts. The integration of spectra measured for 3 minutes under illumination gave almost the same amount of decrease in the average lifetime as obtained in one continuous measurement under illumination. From this, we confirmed that the effect of illumination saturates in 3 minutes.

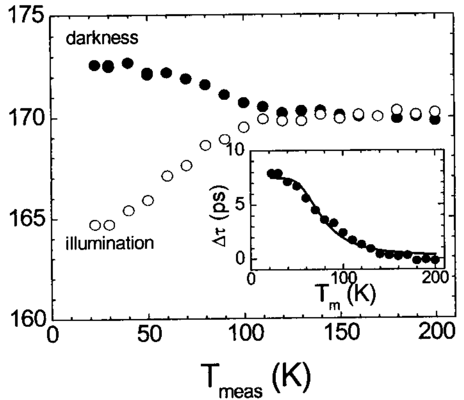

Figure 1 *Average positron lifetime of n-type 6H SiC after irradiation in darkness and under illumination as a function of temperature.*

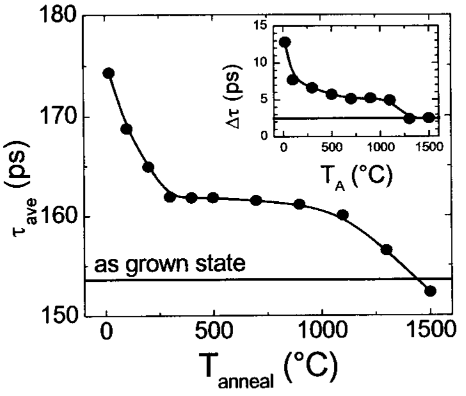

Figure 2 *Average positron lifetime in darkness for n-type 6H SiC after irradiation as a function of temperatures. The inset shows the difference of average positron lifetime between illumination and darkness.*

Results and discussion

Figure 1 shows the average positron lifetime as a function of temperature after irradiation under white light illumination and in darkness. The average lifetime in darkness is almost constant (170 ps) above 110 K and increases below 100 K. The average lifetime before irradiation was 149-145ps at 18-200K. Thus, vacancy-type defects are induced by electron irradiation. It is found that the average lifetime is suppressed upon white light illumination in the temperature range between 18 K and 100 K. An illumination effect is also seen for as-grown state suggesting residual defects after crystal growth. The difference of the average lifetime under illumination and darkness is also plotted in the inset of Fig.1 as a function of temperature. This effect is found to decrease with increasing temperature and disappear above 110 K.

Figure 2 shows the isochronal annealing behavior of average positron lifetime in darkness measured at 18 K. The difference of the average positron lifetimes between darkness and illumination is also shown. From this figure, two annealing steps are seen: The first is from room temperature to 250°C and the second is above 1000°C. Above 1300°C, all the detectable vacancy-type defects disappear [1]. The illumination effect also tends to disappear above 1300°C. Above 400°C, the defect-related lifetime was typically τ_2=185±5 ps either in darkness or under illumination. Based on theoretical calculation [6] and on a positron lifetime experiment combined with electron spin resonance [7], the lifetime of positrons at silicon vacancies is 187-193 ps. Thus, it seems that the major positron trapping center is related to silicon vacancies. Considering that pure silicon vacancies are mobile at 600-800°C [8], the second annealing step above 1300°C is explained as the disappearance of complexes involving silicon vacancies. On the other hand, the intensity I_2 decreases from approximately 45% to 17% by white light illumination. This implies the decrease of trapping efficiency of positrons probably due to the change of the defect charge state. It is important to note that E_1/E_2 defects observed in DLTS experiments also disappear in the same temperature region [9].

Figure 3 shows the difference of the average lifetime under illumination and in darkness as a function of photon energy of the monochromatic light. In the high energy region (>3 eV), the illumination effect disappear due to the indirect transition of electrons from the valence band to the conduction band. It is found that the average lifetime increases from 0.4 eV and tends to saturate above 1 eV. This kind of absorption characteristics is hardly explained as the internal transition of electrons. Probably, electrons are excited from localized levels to the conduction band. The threshold energy for the appearance of the illumination effect is related to the energy level of defects. The data were fitted to the Lucowsky-model [10] which gives the cross section for electron transition from a localized state to a parabolic and isotropic band. The threshold energy is determined to be

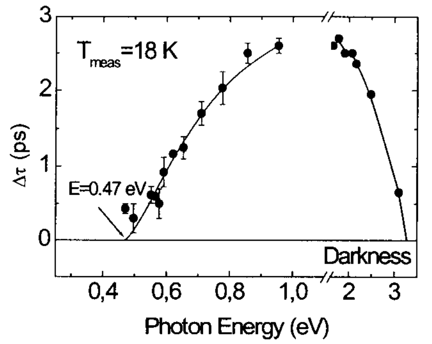

Figure 3 ***Difference of average positron lifetimes under illumination and in darkness as a function of photon energy.***

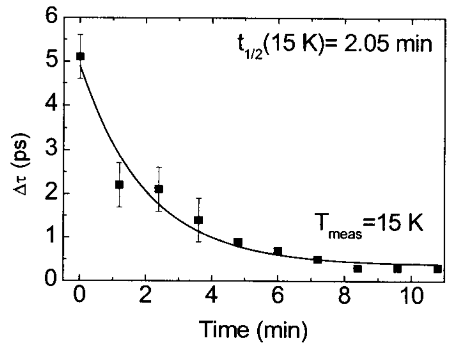

Figure 4 Average positron lifetime in darkness after illumination as a function of time.

E=0.47eV from the fitting as shown in Fig.3. DLTS studies showed that the energy level of E_1/E_2 is located at 0.35-0.4eV below the bottom of the conduction band [4, 9]. The observed threshold energy seems to be a little bit higher than this energy level. However, considering the configurational coordinate diagram by Hemmingson [4], the energy which is required for vertical electron transition from ground state to conduction band should be higher than the energy level observed by conventional DLTS experiments. This allows us to conclude that the observed threshold energy (0.47 eV) might be related to the E_1/E_2 level.

In Figure 4, the decay of illumination effect is presented for the sample temperatures at 15 K. It is found that the illumination effect is persistent for some time and vanishes during 10 minutes at this temperature. This is probably due to the small energy barrier between the excited state and ground state as proposed by Hemmingson [11].

Summary

In summary, we performed positron lifetime measurements with n-type 6H SiC after 2 MeV electron irradiation in darkness and under illumination. The average lifetime was found to decrease between 18 K and 200 K. After the 1300°C annealing, vacancy-type defects and the illumination effect disappear. The illumination with the photon energy above 0.47 eV gives rise to the change of charge state and hence the positron lifetime decreases. This illumination effect disappears in 10 minutes at 15 K after switching off the light suggesting the metastability of this defect.

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