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Photoluminescence of Electron- and Neutron-Irradiated n-Type 6H-SiC*

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Abstract: n-type 6H-SiC materials irradiated with electrons having energies of $E_e = 1.7, 0.5$, and 0.4MeV and neutrons are studied via low temperature photoluminescence. For $E_e \geqslant 0.5$MeV electron-irradiated and neutron-irradiated samples, the LTPL emission lines $S_1/S_2/S_3$ at 478.6/483.3/486.1nm are observed for the first time. Thermal annealing studies show that the defects $S_1/S_2/S_3$ disappear at 500℃. However, the well-known D_1-center is only detected for annealing temperatures over 700℃. By considering the threshold displacement energies of E_{min}(C) and $E_{min}(S_i)$ and thermal annealing behavior, it is found that the defects $S_1/S_2/S_3$ are a set of silicon-related primary defects and the D_1-center is a kind of secondary defect.

Key words: 6H-SiC; irradiation; LTPL; defects
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1 Introduction

The material properties of silicon carbide (SiC) semiconductors make them well suited for high-power, high-temperature, high-frequency, and irradiation-hard electronic devices. Because SiC has a wider band gap, higher thermal conductivity, higher breakdown electric field strength, and higher chemical stability than silicon (Si), it is currently used for most power electronic devices[1]. Irradiation creates defects in SiC materials. These defects are very useful in carrier lifetime control, but most often they are unwanted by-products because they influence the material properties. Furthermore, modern SiC devices are used very widely in irradiation environments. Therefore, in recent years irradiation-induced defects in SiC have been intensively studied using different methods[1~13]. Among these defects are ED1($\sim E_C - 0.27$eV), Ei ($\sim E_C - 0.51$eV), E1/E2($\sim E_C - 0.34/0.44$eV, called Z1/Z2 for 4H-SiC), Z1/Z2($\sim E_C - 0.58/0.72$eV, called E1/E2 for 4H-SiC) which are monitored by deep-level transient spectroscopy (DLTS)[2~6], and D_1-center ($L_1/L_2/L_3$ or L_1 called 4H-SiC) as main signals detected by low-temperature photoluminescence spectroscopy (LTPL)[1,7~10].

In this work, intrinsic defects in n-type 6H-SiC samples induced by electron and neutron-irradiation were studied using the LTPL technique.

2 Experiment

The n-type 6H-SiC samples used in this experiment are commercially available epiwafers from CREE Research, Inc. They have a crystalloid orientation of (0001) and a 5μm-thick nitrogen-doped epilayer on n^+-type 6H-SiC substrate. The nitrogen donor concentrations are 9×10^{15} and $6.6\times10^{18}\mathrm{cm^{-3}}$ in the epilayer and the substrate, respectively. Electron irradiation was carried out with energies of 1.7MeV (dosage of $4.5\times10^{15}/\mathrm{cm^2}$), 0.5MeV (dosage of $3\times10^{16}/\mathrm{cm^2}$), and 0.4MeV (dosage of $3\times10^{15}/\mathrm{cm^2}$), respectively; and the slow-neutron irradiation dose was $1.0\times10^{15}/\mathrm{cm^2}$. Isochronal thermal annealing was performed in nitrogen atmosphere at temperatures from 350 to 1100℃ for 30min.

LTPL measurements were performed at 3.5, 5, and 5.9K, and a 325nm wavelength He-Cd laser was used as the excitation light source in the PL

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measurements. For the measurements at 3.5 and 5.9K, the LTPL emission was analyzed with a SPEX750M single grating (1200 lines/mm) monochromator and detected with a Hamamatsu R928 photo-multiplier; and for the 5K measurements, the luminescence was detected by a GaAs cathode C31034 photo-multiplier after passing through a H25 monochromator.

3 Results and discussion

Figure 1 shows typical LTPL spectra of the electron-irradiated samples with $E_e = 1.7$MeV (dosage of $4.5 \times 10^{15}/cm^2$), 0.5MeV (dosage of $3 \times 10^{16}/cm^2$), 0.4MeV (dosage of $3 \times 10^{15}/cm^2$), and neutron-irradiated (dosage of $1.0 \times 10^{15}/cm^2$) n-type 6H-SiC samples. From curve *a* in Fig.1, three sets of dominant signals can be clearly observed. First, we see the lines of the famous $4N_0$, which are related to bound exciton recombination at a four-particle neutral nitrogen donor at the three inequivalent lattice sites and are commonly used as indicators for N dopants in SiC[14]. Second, the LTPL emission lines $S_1/S_2/S_3$ at 478.6/483.3/486.1nm (curve *a* in Fig.1) are observed for the first time, which can be clearly seen only for the sample irradiated with electrons having energy $E_e \geqslant 0.5$MeV. The $S_1/S_2/S_3$ signals are not found in the low energy electron irradiated sample ($E_e = 0.4$MeV). This implies that $S_1/S_2/S_3$ are only created with electron energy $E_e \geqslant 0.5$MeV. These are very similar to the well-known D1-center ($L_1/L_2/L_3$) lines at 472.4/476.9/482.5nm. It is seen in curve *d* in Fig.1 that $S_1/S_2/S_3$ were also obtained in the as-neutron-irradiated sample.

The annealing behavior of the irradiated samples was systematically studied as shown in Fig.2. After annealing at 350℃, the defect lines $S_1/S_2/S_3$ became weak and completely disappeared at 500℃. Another set of PL peaks emerged at 472.4/476.9/482.5nm after a higher annealing temperature of 700℃. These lines (L_1, L_2, and L_3) are the well known D_1-center, which can withstand annealing up to 1600℃[8,15]. It can be seen that the $S_1/S_2/S_3$ and the D_1-center are different since the PL lines of the latter located at 472.4/476.9/482.5nm only emerged after annealing at 700℃. It is thus most likely that the $S_1/S_2/S_3$ lines are a set of primary defects, while the D1-center is a kind of secondary defect.

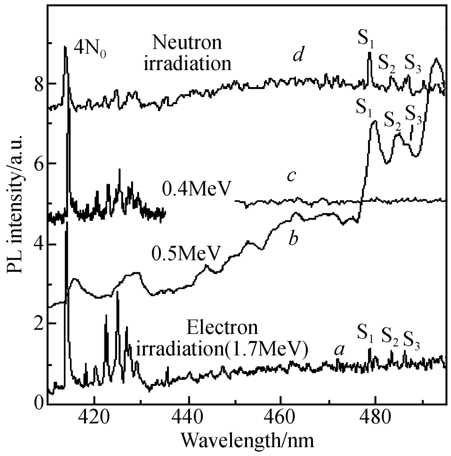

Fig.1 LTPL spectra of 1.7MeV (dosage of $4.5 \times 10^{15}/cm^2$), 0.5MeV (dosage of $3 \times 10^{16}/cm^2$), 0.4MeV (dosage of $3 \times 10^{15}/cm^2$) electron- and neutron-irradiated n-type 6H-SiC

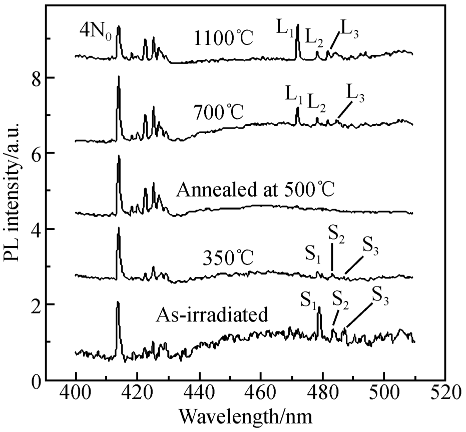

Fig.2 LTPL spectra of neutron-irradiated n-type 6H-SiC at 3.5K before and after annealing

From Fig.1, the series of $S_1/S_2/S_3$ luminescence signals was first observed in the $E_e \geqslant 0.5$MeV electron-irradiated n-type 6H-SiC, which shows that the defects could be produced after the n-type 6H-SiC sample was electron-irradiated with $E_e \geqslant 0.5$MeV. Using both positron lifetime and coincident Doppler broadening techniques, we find that at a low electron irradiation energy of $0.5\text{MeV} > E_e > 0.3$MeV, only V_C is generated, while at higher energies ($E_e \geqslant 0.5$MeV), V_{Si} can also be detected[16]. Thus we suggest that the $S_1/S_2/S_3$ signals might originate from a silicon-related vacancy. The present electron irradiation was performed with an electron accelerator, similarly to the work by Rempel *et al*.[16]. The result is also consistent with that of Rempel *et al*. In other words, that $S_1/S_2/S_3$ are only observed in electron irradiation with energies of $E_e \geqslant 0.5$MeV sample might be due to a silicon-related vacancy.

The $S_1/S_2/S_3$ are absent in the $E_e = 0.4$MeV electron-irradiated sample in PL measurements at 5.9K. Here we discuss the influence of the measurement temperature on PL. Chen *et al*.[6] and Egilsson *et al*.[1] performed PL measurements at 10K and 30K, respectively, showing that temperature change has no influence on the PL signals. Hence the temperature of 5.9K has no influence on the $S_1/S_2/S_3$ lines.

It is noticeable that the shape of curve *b* in Fig.1 is different from that of curves *a* and *c* in Fig.1. This discrepancy is possibly due to the different LTPL equipment as described above.

4 Conclusion

In summary, a new set of defects $S_1/S_2/S_3$ has been observed for the first time in electron-irradiated with $E_e \geqslant 0.5$MeV and neutron-irradiated n-type 6H-SiC, and they were completely removed after annealing treatment at 500℃. The D_1-center appeared after annealing over 700℃. The experimental observations strongly show that the $S_1/S_2/S_3$ PL lines originate from silicon-related primary defects, while the D_1-center is a secondary defect.

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电子和中子辐照n型6H-SiC的光致发光谱*

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摘要： 对用电子能量为1.7，0.5和0.4MeV的电子辐照和中子辐照后的n型6H-SiC样品进行低温光致发光研究.对于$E_e \geqslant 0.5$MeV电子辐照和中子辐照后的样品，首次发现了位于478.6/483.3/486.1nm的$S_1/S_2/S_3$谱线.对样品进行热退火研究表明$S_1/S_2/S_3$谱线在500℃下消失，而退火温度高于700℃时D_1中心出现.考虑到产生C空位和Si空位所需的位移阈能以及热退火行为，说明$S_1/S_2/S_3$为初级Si空位初级缺陷，而D_1中心为二次缺陷.

关键词： 6H-SiC；辐照；LTPL；缺陷

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