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Characterization of Process-Induced Defects in SiC MOSFETs by Cross-Sectional Cathodoluminescence

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Abstract

Cross-sectional cathodoluminescence (CL) was applied to silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs). The L_1 line at 426 nm and a broad luminescence around 430–470 nm were observed. The L_1 line originates from the defect that is produced by the ion-implantation process. The CL spectra and the monochromatic CL images indicate that the defects produced by the ion-implantation remain and diffuse in the SiC epitaxial layer. The generation, annihilation, and evolution mechanism of the defects are discussed.

1. Introduction

Power semiconductor devices are key components for highly efficient energy conversion systems. Silicon carbide (SiC) is one of the wide bandgap semiconductors and has many advantages suitable for power-device application. Though many studies have been carried out to reduce the defects in SiC power devices, the device performance does not reach its theoretical limit. Defect-characterization techniques play an important role to decrease the residual defects and improve device performance. Cathodoluminescence (CL) is powerful techniques to characterize optically active defects and suitable for device characterization since it has high spatial resolution [1–4].

In this paper, we applied cross-sectional CL measurements to SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) and investigated the residual defects. We discuss the generation, annihilation, and evolution mechanism of the defects in the SiC devices.

2. Experiment

Devices used in this study were commercially available 1200 V SiC MOSFETs with TO-247 discrete package. We mechanically cut the packages and polished the cross-section using argon ion beam. We checked the quality of the cross-sectional surface by the linewidth of Raman lines and found that the high-quality surface is processed by this polishing. A Hitachi S-4300SE scanning electron microscope (SEM) was used as the excitation source. The emitted light was analyzed using a HORIBA Jobin Yvon HR-320 single monochromator equipped with a charge-coupled device (CCD). All spectra were recorded by scanning the electron beam in steps of 400 nm and panchromatic and monochromatic CL images were constructed from each spectrum. The acceleration voltage of the electron beam was 10 kV, and its penetration depth was about 1.1 μm according to the Kanaya-Okayama model [5]. CL measurements were performed at 35 K to reduce nonradiative recombination as much as possible. The carrier distribution of the devices was determined using scanning capacitance microscopy (SCM).

3. Results and Discussion

Figure 1(a) shows the panchromatic CL image near the gate and source region of the SiC MOSFET. The CL intensity is not uniform and weak near the source region. Figure 1(b) shows the CL spectra at the points indicated in Fig. 1(a). The near-band-edge emission, several sharp lines, and a broad luminescence are observed in all spectra. The sharp line at 426 nm is the L_1 no phonon line and several peaks around 430–470 nm are its phonon replicas [6, 7]. The L_1 line is frequently observed in ion implanted and electron irradiated SiC. The D_I center is considered the origin of the L_1 line. This center is well known to be stable up to 1700°C. The anti-site pair and several variations are proposed for the structure of the D_I center [8, 9]. The origin of the broad luminescence around 420–600 nm is probably some kind of donor-acceptor pair emission.

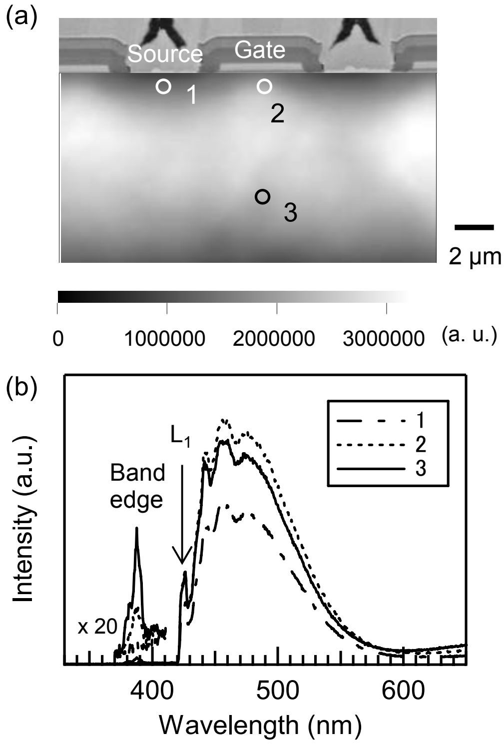

Fig. 1 (a) Panchromatic CL image and (b) CL spectra at the points 1, 2, and 3.

Figure 2 shows the monochromatic CL image of the near-band-edge emission at 387 nm. The CL intensity is weak near the source region. In general, the intensity decay of the band-edge emission indicates that the nonradiative recombination rate is high. The high-dose ion implantation was done only near the source region in the MOSFET. Therefore, the damage induced by the high-dose ion implantation does not fully recovered by the anneal process.

Figure 3 shows the monochromatic CL image of the L_1 line. The intensity is normalized by that of band-edge emission. The intensity of the luminescence from defects can reflect the amount of their defects. However, the intensity is also affected by the amount of nonradiative recombination centers. Therefore, normalized intensity is more appropriate to discuss the amount of the D_I center. In Fig. 3, the relative intensity is not zero at all measurement areas and is strong near the source region. The area where the L_1 line is observed is wider than the area where high-dose ion implantation is done. For example, the L_1 line is observed in the channel region near the gate and even in a depth of 10 μm. This indicates that the high-dose ion implantation and succeeding annealing not only generate the D_I center but also diffuse the defects.

The possible mechanism of the observed distribution of the D_I center is as follows:

(1) The ion implantation creates many types of point defects such as V_{si}, V_C, C_i, Si_i, Si_C, C_{si}.

(2) The annihilation and diffusion of unstable defects take place during the annealing. Some defects transform their structure into more thermally stable defects.

(3) The thermally stable defects such as the D_I center and other nonradiative recombination centers remain after the annealing.

It is not clear whether the D_I center and other nonradiative recombination centers act as device killer defects. However, carrier lifetime can be affected by the D_I center and the switching characteristic of devices can be changed by the distribution of the D_I center. Figures 2 and 3 indicate that the damage by the ion implantation does not fully recovered and the diffusion and the evolution of the defects take place during the annealing. The cross-sectional CL is suitable to visualize the D_I center and other thermally stable defects.

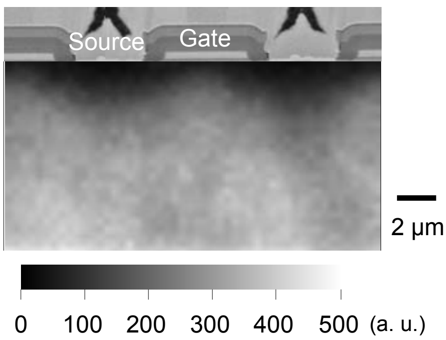

Fig. 2 Monochromatic CL image of the near-band-edge emission at 387 nm.

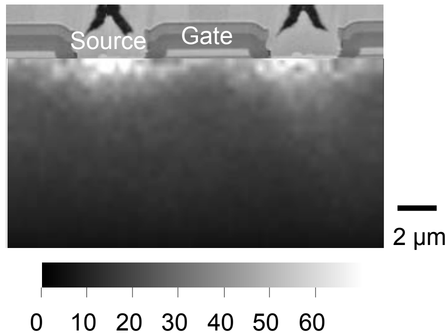

Fig. 3 Monochromatic CL image of the L_1 line at 426 nm. The intensity is normalized by the intensity of the near-band-edge emission to exclude as much as possible the effect of nonradiative recombination.

5. Conclusions

In conclusion, we have applied cross-sectional CL to SiC MOSFETs. In addition to the near-band-edge emission, the L_1 line at 426 nm and the broad luminescence around 430–470 nm were observed. Monochromatic CL images show that the nonradiative recombination rate and the density of the D_I center are high near the source region. Moreover, the CL images also show that the D_I center diffuses in the SiC epitaxial layer during the annealing. The cross-sectional CL method is suitable for characterizing the process-induced defects in SiC MOSFETs and other SiC-based devices.

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