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Semi-Quantitative Determination of Radiative Recombination Centers in Silicon Power Devices by Cross-Sectional Cathodoluminescence

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1. Introduction

Power semiconductor devices are key components for highly efficient energy conversion systems. Elimination or proper control of crystalline defects in the devices is important to reduce switching losses and on-state losses. A variety of defect-characterization techniques have so far been proposed and used, such as deep level transient spectroscopy (DLTS) [1], photoluminescence (PL) [2], electron spin resonance (ESR) [3], and positron annihilation spectroscopy (PAS) [4].

We have applied cathodoluminescence (CL) to characterize radiative recombination centers in lifetime-controlled insulated gate bipolar transistors (IGBTs) [5]. Although luminescence spectroscopy is powerful techniques, it is not easy to derive quantitative information from luminescence spectra. A main reason is the non-radiative paths of excited carriers due to the presence of deep levels formed by various defects. In particular, a surface recombination process should be taken into account in quantitative discussion because the surface of devices has much damage formed during their manufacturing processes.

In this paper, we show a procedure to derive semi-quantitative determination of radiative recombination centers from cross-sectional CL measurements by considering the surface recombination.

2. The Model of Surface Recombination

The CL intensity is generally proportional to the excess minority carrier concentration under low beam current. Therefore, the non-radiative recombination at the surface suppresses the CL emission near the surface. In the silicon (Si) based devices, the surface recombination process should be taken into account since the minority carrier diffusion length are relatively large as compared to those of semiconductors having direct band gaps. Figure 1 shows a semi-infinite n-type semiconductor irradiated uniformly where surface recombination is introduced at one end of the sample. The hole concentration $p_n(x)$ is given by solving the following minority carrier diffusion equation [6, 7]:

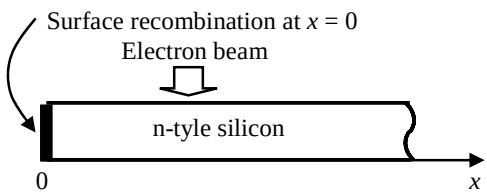

Fig. 1 Model of surface recombination.

$$\frac{\partial p_n(x)}{\partial t} = D_p \frac{\partial^2 p_n(x)}{\partial x^2} + G_L - \frac{p_n(x) - p_{no}}{\tau_p} = 0, \quad (1)$$

where G_L is the generation rate of electron-hole pairs due to light, D_p is the hole diffusion coefficient, τ_p is the hole lifetime, and p_{no} is the hole density at thermal equilibrium. Equation 1 is derived from general continuity equations by assuming that the electric field is zero and the generation level is low. The solution of eq. (1) under proper boundary conditions is

$$p_n(x) = p_{no} + \tau_p G_L \left(1 - \frac{S}{1+S} e^{-x/L_p}\right), \quad (2)$$

where L_p is the minority carrier diffusion length, i.e., $L_p^2 = D_p \tau_p$, S is the reduced recombination velocity, i.e., $S = s_p \tau_p / L_p$, and s_p is the surface recombination velocity. Then, the CL intensity decay $\Delta I(x)$ by the surface recombination is written by the following simple equation:

$$\Delta I(x) = \frac{S}{1+S} e^{-x/L_p} . \quad (3)$$

3. Experimental Procedure

The device used in this study is commercially available 600 V punch-through planar IGBT with lifetime control by electron irradiation. CL measurements were applied to the cross-section of the n-drift layer in the IGBT. All CL measurements were performed at 30 K. The acceleration voltage was 30 kV, whose penetration depth was about 9.3 μm according to the Kanaya-Okayama model [8].

4. Results and Discussion

Figure 2 shows the cross-sectional CL spectra of the n-drift layer. Several sharp peaks and a broad band at around 1200-1400 nm are observed. TO denotes the transverse-optical phonon replica of the band-to-band transition. *X*, *W*, and *C* lines are known to originate from defects produced by electron irradiation [2]. *W* and *X* centers are considered to related to silicon self-interstitials and *X* center is involved larger interstitial cluster than *W* center [9, 10]. *C* center is well recognized as interstitial oxygen and carbon complexes in the form C_iO_i [2].

The intensity of the TO line as a function of the position is shown in Fig. 3. TO line decreases near the surface (gate).

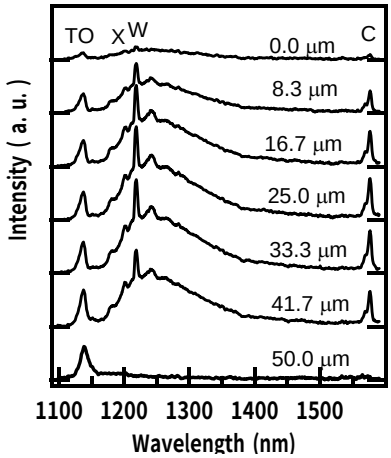

Fig. 2 CL spectra in the n-drift region of the IGBT.

This is mainly because the decrease of excess minority carrier by surface recombination. The decrease of measurement volume must also be considered at a position less than electron beam range. However, the beam range in this experiment is about 9.3 μm, and the decrease of measurement volume is not the main cause of intensity decay. We estimated the effect of surface recombination according to a least-squares fit using eq. (3). From this fitting, the reduced recombination velocity S= 129.5 and the hole carrier diffusion length L_p= 15.3 μm are obtained. Figures 4 and 5 are the experimental peak intensities and corrected intensities of the *W* and *X* lines using above parameters, respectively. The effect of surface recombination is eliminated as much as possible in this correction, and these corrected intensity distributions are considered to defects distributions in the n-drift region. It is considered that electrons that have energies of 1-10 MeV penetrate the entire device and form a non-localized defect distribution. However, the intensity of *W* line is not uniform and its distribution has maximum at about the mid-point in the n-drift region. The *X* line shows a uniform distribution than that of the *W* line. The reason for this intensity decay of the *W* line is not fully understood, but it is probably due to the interaction of other point-like defects and impurities near the surface. The small self-interstitial clusters interact with impurities or other defects near the surface more easily than more large self-interstitial clusters, which is the origin of *X* line.

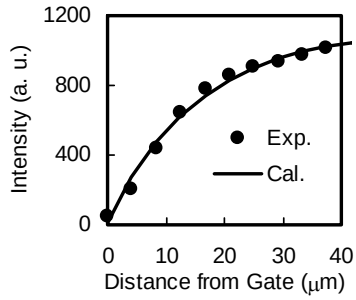

Fig. 3 Experimental peak intensity of the TO line and a best fit with eq. (3).

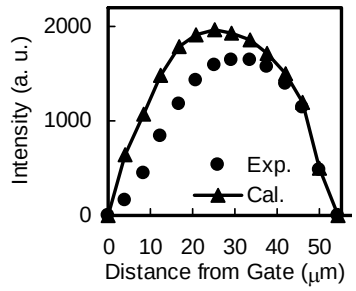

Fig. 4 Experimental peak intensity and a corrected intensity of the *W* line.

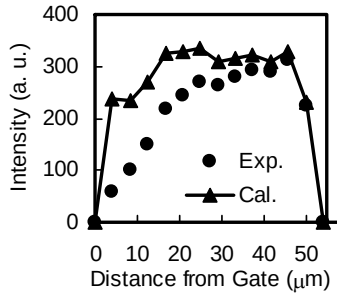

Fig. 5 Experimental peak intensity and a corrected intensity of the *X* line.

5. Conclusions

In conclusion, we have developed a procedure to obtain semi-quantitative distribution of radiative recombination centers in Si power devices from cross-sectional CL measurements by considering the non-radiative recombination at the surface of the devices. This procedure is applicable to not only power devices but also to other devices such as large-scale integration (LSI), image sensors, and Si solar cells.

References

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