New method of carrier lifetime measurement is proposed for accurate power device simulation which requires the values of independent electron ($\tau_n^+$) and hole ($\tau_p^+$) lifetimes. Reverse recovery time and the electron beam-induced junction current of Si p'M diodes were measured to obtain the high injection carrier lifetimes ($\tau_n^+$) and $\tau_p^+$, respectively. $\tau_n^+$ were deduced by extracting $\tau_p^+$ from $\tau_n^+$ on the basis of Shokley-Read-Hall theory. $\tau_{n/p}$ of the non-irradiated samples and samples irradiated at electron fluxes of $3 \times 10^{13}$, $5 \times 10^{13}$ and $7 \times 10^{13} \text{cm}^{-2}$ were 3.1ns, 600ns, 360ns and 300ns, respectively. For the same samples, $\tau_p^+$ were 2.6ns, 2.6ns, 5ns and 3ns, respectively. These results indicate that $\tau_n^+/\tau_p^+$ values are about 1 for non-irradiated samples and 7 to 9 for electron-irradiated samples.

**INTRODUCTION**

It is known that carrier lifetime plays a dominant role in determining Si device characteristics. Therefore, it is very important to evaluate carrier lifetime as well as to control it in order to improve device characteristics. To evaluate carrier lifetime, many methods including photo-conduction [1], reverse recovery time (RRT) [2], open-circuit voltage decay (OCVD) [3], scanning electron microscopy (SEM) [4], microwave reflection [5], and infrared light absorption [6], have been proposed. Even now, these various methods have not been unified into one technique, and that best suiting the device to be fabricated is generally employed. When Si power devices are fabricated, RRT and OCVD have usually been employed to evaluate carrier lifetime. Using these two methods, however, high injection conditions are attained only if the samples are of ordinary size (several square milimeters), so, it is difficult to evaluate electron ($\tau_n^+$) and hole ($\tau_p^+$) lifetimes separately. $\tau_n^+/\tau_p^+$ values affect very much the results of power device simulation [7]. Therefore, it is earnestly expected that $\tau_n^+$ and $\tau_p^+$ are separately obtained by experiments. In the present work, non-irradiated and electron-irradiated Si p'M diodes, which have the simplest structure of all Si power devices, were selected as samples to determine $\tau_n^+/\tau_p^+$ values. The $\tau_n^+$ and $\tau_p^+$ values were obtained separately by combining RRT with SEM for the first time.

**EXPERIMENTAL**

Si p'M diodes were fabricated from magnetic-field Czochralski (MCz)-grown n-type Si substrates. The specific resistivity was 50$\Omega$cm. A boron-doped p+ layer with a surface concentration of $1 \times 10^{15} \text{cm}^{-2}$ and a phosphorous-doped n+ layer with a surface concentration of $1 \times 10^{16} \text{cm}^{-2}$ were obtained using conventional diffusion processes. The thicknesses of the p+, n and n+ in the samples for current versus voltage (I-V), DLTS and RRT experiments were 25, 600nm and 25m, respectively. Those in the samples for the SEM experiments were 25, 250 and 25m, respectively. In both RRT and SEM experiments, the n-layer carrier lifetime was measured. The n-layer carrier concentration was $1 \times 10^{14} \text{cm}^{-3}$. Two kinds of Si p'M diodes were irradiated with an electron beam with a flux of $3 \times 10^{12}$, $5 \times 10^{13}$ and $7 \times 10^{13} \text{cm}^{-2}$. Eight kinds of sample, including non-irradiated ones, were fabricated. The junction area was 8.3mm$^2$.

The RRT measurement system consisted of two parts. The first part causes an electric current to flow through Si p'M diodes. Forward current (I$p$) was adjusted to a value at which the carrier density reached $10^{15} \text{cm}^{-3}$ so that high injection conditions were fulfilled. The second part applied a reverse bias ($V_R$) to Si p'M diodes. The applied $V_R$ was adjusted to give a linear decrease in current. The switching time of both parts was controlled by bipolar transistors.

The equipment employed for SEM was a Hitachi S-570. The electron beam-induced junction current (EBIC) created by irradiation of a cleaved face of a Si p'M diode was measured with an accelerating voltage of 20kV, a filament current of 100mA and a radiated area diameter of 100um.
RESULTS AND DISCUSSION

Figure 1 shows I-V characteristics of the diodes with and without electron irradiation. In the investigated voltage range, the current at a fixed voltage increased notably upon electron irradiation. Little difference was found among the 3, 5 and 7 x $10^{13}$ cm$^{-2}$ electron-irradiated samples. This current increase can be attributed to the creation of deep levels in the Si p-n-n+ diodes.

Figure 2 shows the DLTS spectrum of the sample irradiated at 7 x $10^{13}$ cm$^{-2}$. Reverse and pulse voltages were -10 and 10V. The pulse width and rate window were 1ms and 200ns$^{-1}$. Two peaks were observed at 112 and 224K. It is reasonable to assume that they are electron traps in the n region, not hole traps in the p+ region. As shown in the figure, this speculation is supported by the fact that A and B have nearly equal concentrations and two questions remain. One is that their 0.13eV, 0.23eV and 0.41eV values were determined by the $E_B$ and $E_H$ values of the non-irradiated sample and $K_1$ is a constant. The dashed line was drawn through the four points by least squares analysis, and the points barely deviate from the line. This shows that eq.(2) is fulfilled.

Figure 6 is a plot of $1/\tau_\text{H}$ versus radiation flux (Q). Error bars show the maximum and minimum value for five pellets. $1/\tau_\text{H}$ is thought to be described by the following equation:

$$1/\tau_\text{H} = 1/\tau_\text{H}(B) + K_1Q$$

where $\tau_\text{H}(B)$ is $\tau_\text{H}$ of the non-irradiated sample and $K_1$ is a constant. The dashed line was drawn through the four points by least squares analysis, and the points barely deviate from the line. This shows that eq.(2) is fulfilled.

Figure 7 shows EBIC waveforms for the samples with thicker n-layers. Left and right sides represent n- and p-layers, respectively. The samples with thinner n-layers were not employed in the EBIC experiments because their EBIC waveforms were not triangular but trapezoidal, with the shorter parallel side of the trapezoidal waveforms coinciding with n-layer thickness. It is necessary that EBIC only comprises hole current in order to obtain hole diffusion length ($L_p$) and $\tau_\text{p}$. In the case of samples with thinner n-layers, however, not only did a hole current flow from the n-layer to the p-layer, but also an electron current flowed from the n-layer to the n-layer, because the n-layer was very thin and there was a difference in Fermi energy between the n

(1)

$$N_\text{A} = 0.36 \times Q$$

These results indicate that A and B have the same origin, and are induced by electron irradiation. Evwaraye and Baliga [8] also observed three electron traps with $\Delta E$ of 0.13, 0.23 and 0.41eV in 1.3MeV electron-irradiated Si p+n+m+ diodes. They attributed them to the oxygen-vacancy pair (0-V), double negative electron-positron pair (0-V$^-$) and single negative (0-V$^-$) charge states of the divacancy, respectively. They also claimed that [0-V] is the dominant recombination center in the electron-irradiated Si p+n+m+ diodes. It is difficult to compare their results with ours because they did not give an Arrhenius plot in their paper. However, we speculate that our A (0.13eV) and B (0.39eV) are the same as their 0.23 and 0.41eV traps. This speculation is supported by our results which show that A and B have nearly equal concentrations and probably have the same origin (divacancy), although two questions remain. One is that their 0.13eV electron trap (0-V) is not observed in our crystals. This may be because our crystals have much lower oxygen concentrations than theirs. The other is that there are some differences in $\Delta E$ between their results and ours. In the early days of DLTS studies, correlating the sample temperature with the thermocouple was a great problem. Therefore, these $\Delta E$ differences can likely be attributed to this problem.
and n+ layers. Therefore, it seems that EBIC waveforms became trapezoidal for samples with thinner n-layers. No electron current flowed materially in samples with thicker n-layers because created electrons in the n-layer disappeared until reaching the n+-layer. To obtain \( L / \tau_p \) we used the following equation:

\[
L / \tau_p = (D \tau_p)^{1/2}
\]

(3)

where \( D \) is the hole diffusion constant, assumed to be 12cm\(^2\)-sec\(^{-1}\). Five points on one pellet for each sample were measured. Average \( \tau_p \) and the scatter from the average were determined. The average \( \tau_p \) values of (a), (b), (c) and (d) were 2.6ns, 72ns, 51ns and 33ns, respectively. The maximum scatter from the average was 50%, 36%, 18% and 21%, respectively.

Figure 8 shows \( 1/\tau_p \) versus \( \Phi \). Error bars represent the maximum and minimum values of the 5 points. \( 1/\tau_p \) is thought to be described by the following equation, as \( 1/\tau_H \) in eq.(2).

\[
1/\tau_p = 1/\tau_p(B) + K_2 \Phi
\]

(4)

where \( \tau_p(B) \) is \( \tau_p \) of the non-irradiated sample and \( K_2 \) is a constant. A dashed line was drawn through the 4 points by least squares analysis, and the 4 points hardly deviate from the dashed line. This shows that eq.(4) is fulfilled.

According to SRH theory [9], \( \tau_H \) coincides with the sum of \( \tau_n \) and \( \tau_p \), that is,

\[
\tau_H = \tau_n + \tau_p
\]

(5)

Using eq.(5), we obtained \( \tau_H \) by extracting \( \tau_p \) from \( \tau_H \) although one problem remains. We obtained \( \tau_H \) for the samples with thinner n-layers and \( \tau_p \) for the samples with thicker n-layers. Therefore, there is a possibility that carrier lifetime differs between samples with different n-layer thickness. However, carrier lifetime is a function of \( \Phi \), at least for irradiated samples, so we can assume that carrier lifetime is the same in samples with different n-layer thickness. Values of \( \tau_H \) for (a), (b), (c) and (d) were 3.1ns, 600ns, 360ns and 300ns, respectively.

Figure 9 shows \( 1/\tau_n \) versus \( \Phi \). \( 1/\tau_n \) is also expected to be described by the following equation as in the cases of \( 1/\tau_H \) and \( 1/\tau_p \).

\[
1/\tau_n = 1/\tau_n(B) + K_3 \Phi
\]

(6)

where \( \tau_n(B) \) is \( \tau_n \) of the non-irradiated sample and \( K_3 \) is a constant. A dashed line was drawn through the 4 points by least squares analysis, and the 4 points lie almost on the line. This shows that eq.(6) is fulfilled, as are eqs.(2) and (4).

Table 1 summarizes the average \( \tau_n \), \( \tau_p \) and \( \tau_n/\tau_p \) values.

**References**

Fig. 2 DLTS spectrum of the $7 \times 10^{13}$ cm$^{-2}$ electron-irradiated sample.

Fig. 3 Arrhenius plot of A and B.

Fig. 4 Relationship between electron trap concentration ($N_T$) and electron beam flux ($\Phi$)

Fig. 5 Waveforms of RRT of samples with thinner n-layers. (a), (b), (c) and (d) correspond to non-irradiated, $3 \times 10^{13}$ cm$^{-2}$, $5 \times 10^{13}$ cm$^{-2}$ and $7 \times 10^{13}$ cm$^{-2}$ electron-irradiated samples, respectively. One vertical division represents 100 mA, whereas one horizontal division reveals 100 ns, respectively.

Fig. 6 $1/N_T$ versus $\Phi$. Error bars represent the maximum and minimum values from 5 pellets.
Fig. 7 EBIC waveforms for samples with thicker n-layers. (a), (b), (c) and (d) correspond to non-irradiated, $3 \times 10^{13} \text{cm}^{-2}$, $5 \times 10^{13} \text{cm}^{-2}$ and $7 \times 10^{13} \text{cm}^{-2}$ electron-irradiated samples, respectively. Left and right sides represent n- and p-layers, respectively.

Fig. 8 $1/\tau_p$ versus $\Phi$. Error bars show the maximum and minimum values for 5 points.

Fig. 9 $1/\tau_n$ versus $\Phi$.

Table 1 Summary of $\tau_n$, $\tau_p$ and $\tau_n/\tau_p$.

<table>
<thead>
<tr>
<th>Radiation Flux ($\text{cm}^{-2}$)</th>
<th>$\tau_n$ (ns)</th>
<th>$\tau_p$ (ns)</th>
<th>$\tau_n/\tau_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Irradiated</td>
<td>3100</td>
<td>2600</td>
<td>1.2</td>
</tr>
<tr>
<td>$3 \times 10^{13}$</td>
<td>600</td>
<td>72</td>
<td>8.3</td>
</tr>
<tr>
<td>$5 \times 10^{13}$</td>
<td>360</td>
<td>51</td>
<td>7.1</td>
</tr>
<tr>
<td>$7 \times 10^{13}$</td>
<td>300</td>
<td>33</td>
<td>9.1</td>
</tr>
</tbody>
</table>