Difference between Traps Determined from Transient Capacitance and Transient Reverse Current

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The densities and energy levels of traps in silicon pin diodes are determined using the transient capacitance method (ICTS: isothermal capacitance transient spectroscopy) as well as the transient reverse current method (DCTS: discharge current transient spectroscopy). The traps determined by ICTS are located in the i layer (i.e., the n⁻ region) and affect the steady-state reverse current (i.e., a generation current). Conversely, the traps determined by DCTS are probably located at the surface of the substrate.

KEYWORDS: transient reverse current, steady-state reverse current, pin diode, determination of trap densities and trap levels, discharge current transient spectroscopy, isothermal capacitance transient spectroscopy, surface states, generation centers

One of the authors has developed a method for graphically determining the densities \(N_t\) and energy levels \(E_t\) of traps related to the transient current, called discharge current transient spectroscopy (DCTS).\(^1\)\(^-\)\(^3\) Although DCTS was proposed for the determination of such in insulators, it can determine \(N_t\) and \(E_t\) of traps \(T_{\text{DCTS}}\) related to the transient reverse current in diodes. Another method, isothermal capacitance transient spectroscopy (ICTS),\(^4\)\(^-\)\(^5\) can determine \(N_t\) and \(E_t\) of traps \(T_{\text{ICTS}}\) related to the transient capacitance in diodes. Using silicon (Si) pin diodes for X-ray detectors, we investigate the difference between traps determined by DCTS and those determined by ICTS. Moreover, we study the relationship between these traps and the steady-state reverse current.

The resistivity and thickness of phosphorus (P)-doped n-type Si substrate (i.e., an i layer) were approximately 2 kΩ cm and 300 μm, respectively. A 0.2-μm-thick n⁺ layer was formed on one side of the substrate by the thermal diffusion of P, and then 0.15-μm-thick p⁺ layers with a circle 3 mm in diameter were formed on the other side by the thermal diffusion of boron (B). The junction area \(S\) of the pin diode was 7.1 mm². Except the p⁺ regions, the surface of this side was passivated with silicon dioxide (SiO₂). Chips with an area of 5 mm x 5 mm were fabricated by dicing the substrate. The diced edge was not passivated.

The current–voltage \((I–V)\) characteristics and the transient reverse currents were measured using a Keithley 236 Source Measure Unit. The capacitance–voltage \((C–V)\) characteristics and the transient capacitance were measured at 1 MHz using a Horiba DA-1500.

From the slope of the \(1/C^2–V\) curve, the density \(N_{\text{sum}}\) was determined to be \(2.4 \times 10^{12} \text{cm}^{-3}\). \(N_{\text{sum}}\) indicates the sum of the donor density \(N_D\) and the density of positively charged traps in the depletion region.

The ICTS signal is defined by\(^4\)

\[
S(t) = \frac{C'(t)}{t} \quad \text{(1)}
\]

where \(C'(t)\) is the transient capacitance after a reverse bias voltage \(V_R\) is applied to the pin diode \((t = 0)\). Since

\[
S(t_{\text{peak}}) = N_t \frac{C_{\infty}^2 \exp(-1)}{N_{\text{sum}}} \quad \text{(2)}
\]

at the peak time \((t_{\text{peak}} = 1/e_t)\), the values of \(N_t\) and \(e_t\) can be determined from \(S(t_{\text{peak}})\) and \(t_{\text{peak}}\), respectively, where \(C_{\infty}\) is the steady-state capacitance at \(V_R\) and \(e_t\) is the emission rate for electrons.

Figure 1 shows the ICTS signal at \(V_R = -30\) V at room temperature. The values of \(t_{\text{peak}}\) and \(N_t\) were obtained to be \(1.0 \times 10^{-3}\) s and \(1.2 \times 10^{12} \text{cm}^{-3}\), respectively. From the filling pulse measurement,\(^4\) the capture cross section \((\sigma_c)\) of \(T_{\text{ICTS}}\) was determined to be \(1.4 \times 10^{-15} \text{cm}^2\). Using \(\sigma_c\)\(^4\) \(E_t\) was determined to be \(E_C = -0.53\) eV, where \(E_C\) is the energy level at the bottom of the conduction band. Judging from the magnitude of \(\sigma_c\), \(T_{\text{ICTS}}\) is neutral in the depletion region and is negative in the bulk. Therefore, \(N_D\) is \(2.4 \times 10^{12} \text{cm}^{-3}\), and the electron concentration \((n)\) in the conduction band is \(1.2 \times 10^{12} \text{cm}^{-3}\) in the bulk.

The DCTS signal is defined by\(^1\)\(^-\)\(^3\)

\[
D(t) = t \left[ I_{\text{dis}}(t) - I_{\infty} \right] \frac{\exp(1)}{q} \quad \text{(3)}
\]

where \(I_{\text{dis}}(t)\) is the transient reverse current after \(V_R\) is applied to the pin diode \((t = 0)\), \(I_{\infty}\) is the steady-state reverse current at \(V_R\) and \(q\) is the magnitude of an electron charge. The peak value of \(D(t)\) is expressed as\(^3\)

\[
D(t_{\text{peak}}) = A_t \quad \text{(4)}
\]

where \(t_{\text{peak}} = 1/e_t\) and \(A_t\) is the number of captured carriers at \(t = 0\).

Figure 2 shows the temperature dependence of DCTS signals at \(V_R = -100\) V. Each measurement was carried out after the diode was kept at 0 V for one day. From the peak value, \(A_t\) of \(T_{\text{DCTS}}\) was determined to be about \(6.8 \times 10^{13}\) electrons. If \(T_{\text{DCTS}}\) is uniformly located in the i layer, \(N_t\) is determined from the\(^3\)

\[
1/\tau = \frac{dS(t)}{dt} \quad \text{(5)}
\]

where \(S(t)\) and \(\sigma_c\) are the ICTS signal and the capture cross section, respectively. In the case of \(T_{\text{DCTS}}\), the time constant \(\tau\) is determined to be 300 K.

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\*Web site: http://www.osakac.ac.jp/labs/matsuura/
From the $1/T^2$ peak $–1/T$ plots, the values of $E_t$ and $\sigma_t$ for $T_{\text{DCTS}}$ were determined to be $E_C = -0.54$ eV and $1.4 \times 10^{-19}$ cm$^2$, respectively.

Since the reverse current was proportional to the square root of the reverse voltage, the generation current ($I_g$) was considered to be dominant. The effective lifetime ($\tau_g$) was determined to be $2.7 \times 10^{-5}$ s, since

$$I_g = \frac{q n_i W S}{2 \tau_g},$$

(5)

where $n_i$ is the intrinsic concentration of Si and $W$ is the steady-state depletion width.$^{5}$ On the other hand, $\tau_g$ can be approximately calculated using

$$\tau_g \simeq \frac{1}{\sigma_t v_{\text{th}} n_i},$$

(6)

because $E_t$ is located around the midgap, where $v_{\text{th}}$ is the thermal velocity. The values of $\tau_g$ for $T_{\text{ICTS}}$ and $T_{\text{DCTS}}$ are calculated to be $3.0 \times 10^{-5}$ s and $1.1 \times 10^{-7}$ s, respectively. Therefore, $T_{\text{ICTS}}$ is considered to be a generation center.

Since the capture time ($\tau_t$) is given by

$$\tau_t = \frac{1}{n \sigma_t v_{\text{th}}},$$

(7)

the value of $\tau_t$ for $T_{\text{DCTS}}$ was calculated to be $0.30$ s at room temperature, indicating that all $T_{\text{DCTS}}$ can be refilled with electrons at 0 V for a period longer than 0.30 s. After the first DCTS measurement, it was kept at 0 V for 30 min and then the second DCTS measurement was performed. However, the transient reverse current was not observed, indicating that it was difficult to fill $T_{\text{DCTS}}$ with electrons for 30 min at 0 V. This suggests that $T_{\text{DCTS}}$ must be located in the region where $n$ is much lower than $1.2 \times 10^{12}$ cm$^{-3}$ at 0 V.

$T_{\text{DCTS}}$ is considered to be traps located in large-area defects, such as surfaces of the substrate, interfaces between the substrate and the passivation layer, micropiles, and grain boundaries in polycrystals. Since the Si substrate used here is a single crystal of good quality, $T_{\text{DCTS}}$ is considered to be located at the surface of the diced edge or the interface between SiO$_2$ and the Si substrate.

The schematic locations of $T_{\text{DCTS}}$ and $T_{\text{ICTS}}$ are shown in Fig. 3. Both traps capture electrons at 0 V, while they emit electrons at $V_R$. However, it takes a long time for $T_{\text{DCTS}}$ to capture electrons, when the applied voltage changes from $V_R$ to 0 V.

In our Si pin diodes, $N_t$ and $E_t$ of large-area defects (i.e., traps at the surface of the diced edge or at the interface between the Si substrate and the passivation layer) were determined by DCTS, while those of point defects (i.e., generation centers) were determined by ICTS.

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