Jpn. J. Appl. Phys. Vol. 39 (2000) pp. 178–179
Part 1, No. 1, January 2000

Short Note

Investigation of Transient Reverse Currents in X-Ray Detector Pin Diodes by Discharge Current Transient Spectroscopy

Hideharu MATSUURA* and Kazushige SEGAWA
Department of Electronics, Osaka Electro-Communication University, 18-8 Hatsu-cho, Neyagawa, Osaka 572-8530, Japan

(Received September 20, 1999; accepted for publication October 19, 1999)

Transient reverse currents flow in X-ray detector diodes when a high reverse bias (operating voltage) is suddenly applied from 0 V, which leads to problems in the X-ray measurements. Discharge current transient spectroscopy (DCTS) was applied to determine the densities, energy levels and capture cross sections of traps related to the transient reverse currents in the diodes. DCTS analysis revealed one type of trap with $E_C - 0.54$ eV in our silicon pin diodes, where E_C is the energy level at the bottom of the conduction band.

KEYWORDS: transient reverse current, pin diode, determination of trap densities and trap levels, capture cross section, discharge current transient spectroscopy, X-ray detector

Silicon (Si) pin diodes and lithium (Li)-doped Si diodes have been developed for use in X-ray energy spectroscopy. In order to form a wide depletion region, the diode is operated at a reverse bias higher than 100 V. However, when the high reverse bias is suddenly applied from 0 V, a transient reverse current flows, which breaks the junction field-effect transistor connected to the diode. To reduce the transient reverse current, it is necessary to investigate its origin.

One of the authors has developed a simple method for graphically determining the densities and energy levels of traps related to the transient current in capacitors, referred to as discharge current transient spectroscopy (DCTS).[1–5] In this study, we aim to apply DCTS to determine the densities and energy levels of traps related to the transient reverse current in Si pin diodes.

Let us consider the transient reverse current $I_{dis}(t)$ of a pin diode after a high reverse bias (V_R) is suddenly applied from 0 V ($t = 0$ s). $I_{dis}(t)$ consists of two types of currents: (1) a steady-state reverse current (I_R) and (2) a transient reverse current $I_{TR}(t)$ that arises from the emission of charged carriers from traps. The total charge $Q(t)$ of trapped carriers decreases with t as[1–5]

$$Q(t) = \sum_i q N_{ti} \exp(-e_{ti} t), \quad (1)$$

where N_{ti} is the number of carriers captured at the i-th trap at $t = 0$ s, e_{ti} is the emission rate of the i-th trap and q is the magnitude of the electronic charge. Because the decrease of $Q(t)$ results in $I_{TR}(t)$,

$$I_{TR}(t) = -\frac{dQ(t)}{dt} = \sum_i q N_{ti} e_{ti} \exp(-e_{ti} t). \quad (2)$$

To graphically determine N_{ti} and e_{ti} independently, we define a DCTS signal $D(t)$ as[1–5]

$$D(t) \equiv t\,[I_{dis}(t) - I_R]\,\frac{\exp(1)}{q} \quad (3)$$

$$= t \cdot I_{TR}(t)\,\frac{\exp(1)}{q}, \quad (4)$$

which is theoretically expressed using eq. (2) as

$$D(t) = \sum_i N_{ti} e_{ti} t \exp(-e_{ti} t + 1). \quad (5)$$

The function of $N_{ti} e_{ti} t \exp(-e_{ti} t + 1)$ has a peak value of N_{ti} at the peak time ($t_{peaki} = 1/e_{ti}$). From the $D(t)$ curve, therefore, the values of N_{ti} and e_{ti} can be independently determined as follows:

$$e_{ti} = \frac{1}{t_{peaki}} \quad (6)$$

and

$$N_{ti} = D(t_{peaki}). \quad (7)$$

In the case of thermionic emission, the energy level ($E_C - E_{ti}$) of the i-th electron trap can be determined as follows, where E_C is the energy level at the bottom of the conduction band. The thermionic emission rate e_{ti} is given by[6–9]

$$e_{ti} = \nu_{ti} \exp\left(-\frac{E_C - E_{ti}}{kT}\right), \quad (8)$$

where ν_{ti} is the attempt-to-escape frequency of the i-th trap and k is the Boltzmann constant. On the other hand,

$$\nu_{ti} = \sigma_{ti} v_{th} N_C, \quad (9)$$

where σ_{ti} is the capture cross section of the i-th trap, v_{th} is the thermal velocity of electrons and N_C is the effective density of states in the conduction band.[6–9] Since

$$v_{th} = \sqrt{\frac{3kT}{m_n^*}} \quad (10)$$

and

$$N_C = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} M_C, \quad (11)$$

ν_{ti} is expressed as

$$\nu_{ti} = \nu_{t0i} T^2 \quad (12)$$

with

$$\nu_{t0i} = \sigma_{ti} \frac{4\sqrt{6\pi^3} m_n^* k^2 M_C}{h^3}, \quad (13)$$

where m_n^* is the electron effective mass, M_C is the number of equivalent minima in the conduction band, and h is the Planck constant. As a result, the following relationship is obtained:

$$\frac{1}{T^2 t_{peaki}} = \nu_{t0i} \exp\left(-\frac{E_C - E_{ti}}{kT}\right). \quad (14)$$

*Web site: http://www.osakac.ac.jp/labs/matsuura/

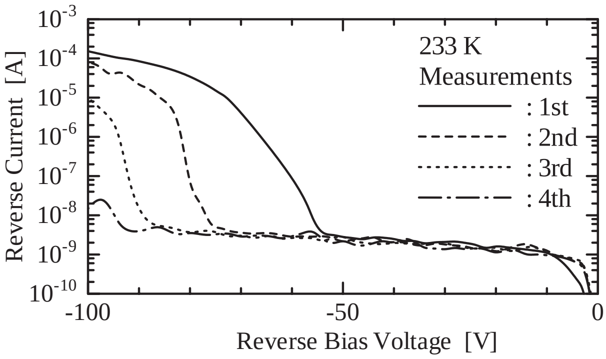

Fig. 1. I–V characteristics for various orders of measurement.

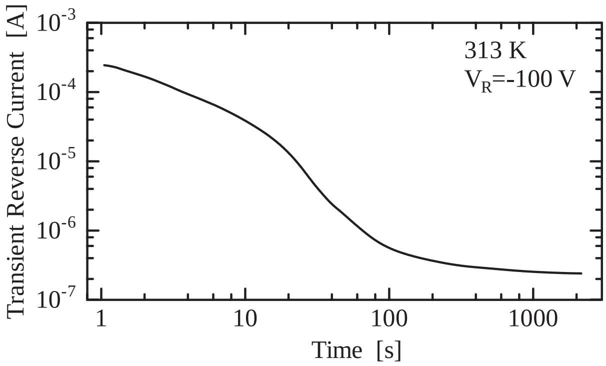

Fig. 2. The transient reverse current after the applied voltage was changed from 0 V to −100 V at 313 K.

Using the Arrhenius plot of $\ln[1/(T^2 t_{\text{peak}i})] - 1/T$, the values of $(E_C - E_{ti})$ and ν_{t0i} can be obtained from the slope and the intercept of the vertical axis, respectively. Using the obtained ν_{t0i} and eq. (13), the value of σ_{ti} can be determined.

The resistivity and the thickness of phosphorus (P)-doped n-type Si substrates (n^- substrates) were approximately $2\,k\Omega\cdot$cm and 300 μm, respectively. The n^- substrate corresponds to the i layer of the pin diodes. The chip size of each pin diode was $5 \times 5\,\text{mm}^2$. The 0.2-μm-thick n^+ layer was formed on one side of the chip by the thermal diffusion of P, and then the 0.15-μm-thick p^+ layer was formed on the other side by the thermal diffusion of boron (B). The n^+ and p^+ regions of the diodes were circular with a diameter of 3 mm. The current–voltage (I–V) characteristics and $I_{\text{dis}}(t)$ were measured using a Keithley 236 source measure unit.

Figure 1 shows the I–V characteristics for various orders of measurement. The solid line represents the I–V curve for the first measurement from 0 V to −100 V. As soon as the first measurement was completed, the second measurement (the broken line) was carried out from 0 V to −100 V. Then the third measurement (the dotted line) and the fourth measurement (the dashed-dotted line) were similarly performed.

In the first measurement, I increased rapidly at $V < -50$ V, and became approximately 1×10^{-4} A at −100 V. As the measurement was repeated, V at which I increased rapidly shifted from a low reverse voltage to a high reverse voltage, and I at −100 V decreased. These results suggest

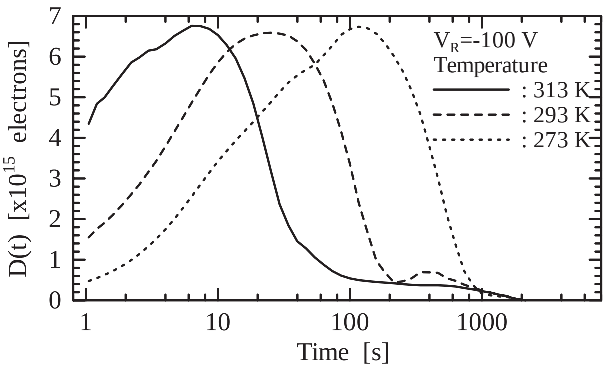

Fig. 3. The temperature dependence of DCTS signals.

that the emission of carriers captured at the traps influences the I–V characteristics.

Figure 2 shows $I_{\text{dis}}(t)$ at 313 K after the applied voltage was changed rapidly from 0 V to −100 V. At $t > 1000$ s, the reverse current was constant, indicating that all trapped electrons had been emitted out.

Figure 3 shows the temperature dependence of DCTS signals. From the peak value, the value of N_t was determined to be about 6.8×10^{15} electrons using eq. (7).

From the slope and the intercept of the vertical axis in the $1/(T^2 t_{\text{peak}}) - 1/T$ plot, the values of $(E_C - E_t)$ and σ_t were determined to be 0.54 eV and $1.4 \times 10^{-19}\,\text{cm}^2$, respectively. The temperature dependence of t_{peak} suggests that the emission of electrons from the traps is thermionic.

In summary, DCTS was found to be useful for determining the densities, energy levels and capture cross sections of traps related to the transient reverse current in pin diodes, and in the Si pin diodes, the trap with $E_C - E_t = 0.54$ eV and $\sigma_t = 1.4 \times 10^{-19}\,\text{cm}^2$ was observed.

The authors would like to thank Dr. K. Nishida and Dr. H. Tomozawa of Kyoto Semiconductor Corp. for the fabrication of Si pin diodes. They also would like to acknowledge Professor K. Taniguchi of Osaka Electro-Communication University and Mr. T. Utaka of Rigaku Industrial Corp. for their support during this work. This work is partially supported by the Japan Science and Technology Corporation.

1) H. Matsuura, M. Yoshimoto and H. Matsunami: Jpn. J. Appl. Phys. **34** (1995) L185.
2) H. Matsuura, M. Yoshimoto and H. Matsunami: Jpn. J. Appl. Phys. **34** (1995) L371.
3) H. Matsuura: Jpn. J. Appl. Phys. **35** (1996) 2216.
4) H. Matsuura: Jpn. J. Appl. Phys. **35** (1996) 4711.
5) H. Matsuura: Jpn. J. Appl. Phys. **36** (1997) 3569.
6) D. K. Schroder: *Semiconductor Material and Device Characterization* (John Wiley, New York, 1998) p. 269.
7) K. F. Brennan: *The Physics of Semiconductors with Applications* (Cambridge University Press, Cambridge, 1999) p. 499.
8) H. Matsuura: J. Appl. Phys. **64** (1988) 1964.
9) H. Matsuura and H. Okushi: *Amorphous and Microcrystalline Semiconductor Devices Vol. II: Materials and Device Physics*, ed. J. Kanicki (Artech House, Boston, 1992) Chap. 11.
10) D. V. Lang, J. D. Cohen and J. P. Harbison: Phys. Rev. B **25** (1982) 5285.