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Development of current-based microscopic defect analysis method using optical filling techniques for the defect study on heavily irradiated high-resistivity Si sensors/detectors

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Abstract

Current-based microscopic defect analysis method such as current deep level transient spectroscopy (I-DLTS) and thermally stimulated current have been developed over the years at Brookhaven National Laboratory (BNL) for the defect characterizations on heavily irradiated ($\Phi_n \geqslant 10^{13}$ n/cm^2) high-resistivity ($\geqslant 2$ kΩ cm) Si sensors/detectors. The conventional DLTS method using a capacitance transient is not valid on heavily irradiated high-resistivity Si sensors/detectors. A new optical filling method, using lasers with various wavelengths, has been applied, which is more efficient and suitable than the traditional voltage-pulse filling. Optimum defect-filling schemes and conditions have been suggested for heavily irradiated high-resistivity Si sensors/detectors.

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Keywords: DLTS; Defects; Detectors; Sensors; Current transient

1. Introduction

Microscopic defect analysis method such as deep level transient spectroscopy (DLTS) and thermally stimulated current (TSC) have been developed and used widely for defect studies on low-resistivity ($<10\,\Omega$ cm) materials and detectors [1,2]. The conventional DLTS method using a capacitance transient is not valid on heavily irradiated high-resistivity Si sensors/detectors since the radiation-induced defect concentration would be much higher than that of the initial doping concentration (about 10^{12} cm^{-3}). In addition, the bulk of the heavily irradiated sensor would be highly compensated, causing frequency-dependent capacitance that is flat at any bias for a frequency > 200 kHz [3]. The new I-DLTS/TSC (current-DLTS/thermally stimulated current) system developed at BNL for defect characterizations on heavily irradiated ($\Phi_n \geqslant 10^{13}$ n/cm^2) high-resistivity ($\geqslant 2$ kΩ cm) Si sensors/detectors, has a temperature range of $8\,\text{K} \leqslant T \leqslant 450\,\text{K}$ and a high sensitivity that can detect a defect concentration of less than 10^{10} cm^{-3} with a background noise as low as 10 fA. A new optical filling method, using

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lasers with various wavelengths, has been applied, and it is more efficient and suitable than the traditional voltage-pulse filling.

2. Modeling

The schematics of defect filling and emission (detrapping) in a Si detector ($p^+/n/n^+$ structure) have been illustrated in Fig. 1 for an electron trap (a) and a hole trap (b). The transport of electrons (or holes) emitted from filled traps can cause a current transient that can be used to study the corresponding defect levels. It has been derived from Ref. [4] that the I-DLTS signal can be expressed as in the following:

$$\delta I_{\mathrm{DLTS}} = \begin{cases} -\frac{1}{2} qAW_nN_t\eta e_n(\mathrm{e}^{-e_nt_1} - \mathrm{e}^{-e_nt_2}) \\ (e_n >> e_p, \text{majority trap}), \\ -\frac{1}{2} qAW_nN_t(1-\eta)e_p(\mathrm{e}^{-e_pt_1} - \mathrm{e}^{-e_pt_2}) \\ (e_n << e_p, \text{minority trap}), \end{cases} \qquad (1)$$

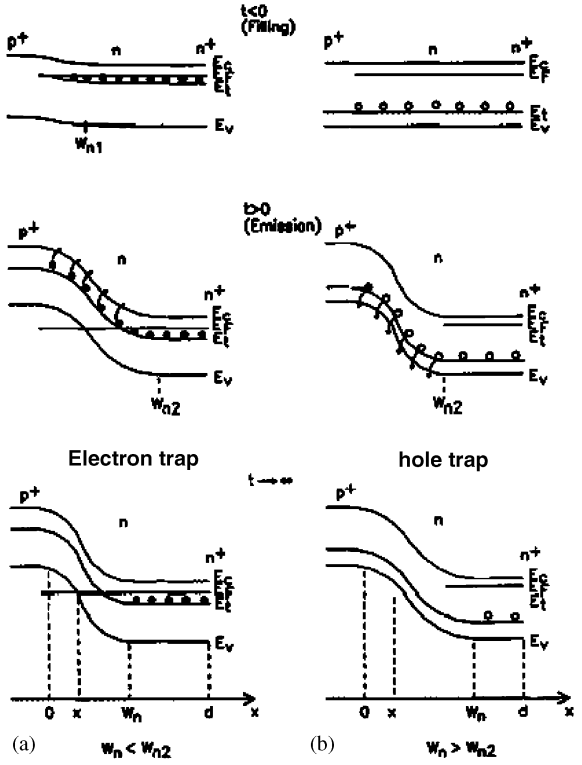

Fig. 1. Energy band diagrams of the defect filling and emission under different bias conditions. (a) for electron traps and (b) for hole traps.

where q is the electronic charge, A the detector area, W_n the detector depletion depth, N_t the total defect concentration of energy E_t in the forbidden energy gap, and η the electron filling percentage given by

$$\eta = \frac{c_nn_0}{c_nn_0 + c_pp_0} \quad (0<\eta<1), \qquad (2)$$

where n_0 and p_0 are non-equilibrium concentration for electrons and holes during filling, respectively, and c_n and c_p are the corresponding capture rate.

The I-DLTS signal is the current transient difference between the two fixed sampling points t_1 and t_2 for a given run in a temperature scan, as shown in Fig. 2. By varying the sampling points, say by changing the ratio of t_2/t_1, one can get a set of I-DLTS spectra that can be used to determine the defect parameters.

It is straightforward to get the defect energy level by making the Arrhenius plot of log (T_mt_1) vs. $1000/T_{\mathrm{m}}$ (T_{m} is the peak temperature), whose slope gives the defect energy level

$$E_{\mathrm{C}} - E_{\mathrm{t}} \ (\text{or } E_{\mathrm{t}} - E_{\mathrm{V}}) = \frac{\text{Slope}}{5.03} \ (\text{eV}) \qquad (3)$$

and the concentration of defect E_{t} can be obtained using

$$N_{\mathrm{t}} = \frac{5.45\delta I^{\mathrm{m}}_{\mathrm{DLTS}}}{qAW_n} t_1 \left(for \frac{t_2}{t_1} \geqslant 4 \right), \text{ both types of traps.} \qquad (4)$$

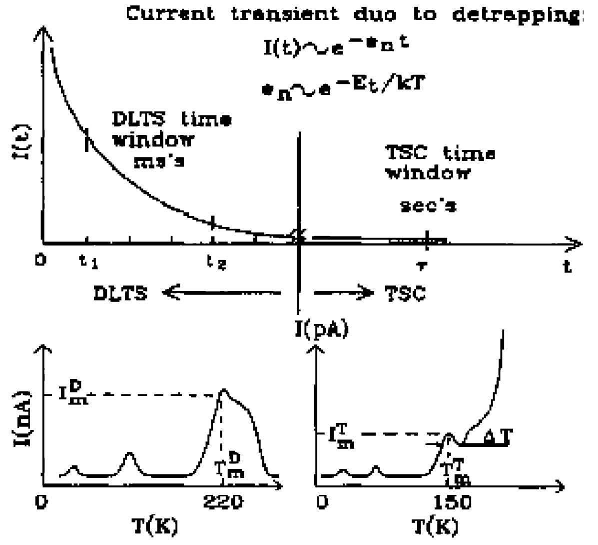

Fig. 2. Illustration of current transient used for I-DLTS and TSC measurements.