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**Determination of the Fermi Level Position for Neutron Irradiated High Resistivity
Silicon Detectors and Materials Using the Transient Charge Technique(TChT)***

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**Determination of the Fermi Level Position for
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Abstract

The transient charge technique (TChT) has been used in this work to study the electrical properties in both space charge region (SCR) and electrical neutral bulk (ENB) of neutron irradiated high resistivity (4-6 kΩ-cm) silicon particle detectors. Detectors irradiated to various neutron fluences were measured by TChT at various biases and temperatures below the room temperature. The Fermi level, obtained from the Arrhenius plot of the time constant of the slow component of the charge shape, has been found to stabilize around $E_c - 0.47$ to 0.50 eV at high fluences ($\Phi_n > 10^{13}$ n/cm²). The resistivity of the ENB has been found greater than 300 kΩ-cm at high fluences.

Summary

Recently, much of the interest on the neutron radiation effects on high resistivity p⁺/n junction detectors have been concentrated on the high fluence ($\Phi_n > 10^{13}$ n/cm²) neutron induced changes of detector and material electrical properties, in the wake of the anticipated high radiation environment (10^{14} n/cm² in ten years) in the newly proposed Large Hadron Collider. The effective doping concentration (sometime also called : effective impurity concentration) N_{eff} in the space charge region (SCR), which determines the detector full depletion voltage V_d , as a function of neutron fluence has been mainly studied by the capacitance-voltage (C-V) technique^[1-4], although there are some recent attempts using the transient current techniques (TCT), such as alpha^[5] and laser^[6] induced current shapes, to obtain V_d and N_{eff} . The C-V technique becomes less reliable at high neutron fluences due to high leakage current and frequency dependence^[2]. The material properties, or the

electrical neutral bulk (ENB) properties, have been studied by entirely different techniques such as the four-point probe approach^[7], the resistor structure approach^[8], and the Hall effect approach^[9-10]. All these approaches, however, are highly limited by the surface conditions and by the contact problems (ohmic contacts required). In this paper, we will present the data of detector SCR properties such as N_{eff} , and ENB properties such as the position of the Fermi level, resistivity, and free carrier concentrations (n and/or p) as a function of neutron fluence using the transient charge technique (TChT).

The laser TCT/TChT set-up in BNL, designed in FTI and improved in BNL under the current PTI-BNL collaboration, is consist of a GaAs laser diode ($\lambda \sim 0.82$ μm), a nanosecond pulse generator and a current amplifier supplying laser pulse, an oscilloscope, a temperature controller, and a L-N₂ dewar for low temperature measurements.

An example of the laser induced current shape is shown in Fig. 1 for a non-irradiated detector. The detector was biased in a partially depleted mode and the laser illumination was on the p⁺ side for which the current shape is mainly electron induced current. For a non-irradiated detector, the electron current shape follows the exponential decay $e^{-t/\tau}$ and the time constant can be written as^[6,11]:

$$\tau = \frac{\epsilon\epsilon_0}{e\mu N_{eff}} \cdot \frac{d}{w} \quad (1)$$

where d is the detector thickness, w the depletion width:

$$w = \sqrt{\frac{2\epsilon\epsilon_0 V}{eN_{eff}}} \quad (2)$$

where V is the detector bias. The time constant for a non-irradiated detector is therefore dependent on both V and N_{eff} :

$$\tau = \frac{d}{\mu} \cdot \sqrt{\frac{\epsilon\epsilon_0}{2eN_{eff}}} \cdot \frac{1}{\sqrt{V}} \quad (3)$$

Fig.2 shows $1/\tau^2$ for a non-irradiated detector as a function of the detector bias V . A clear linear dependence gives a N_{eff} of about 7.3×10^{11} /cm³, very

close to the value of $7.0 \times 10^{11} \text{ /cm}^3$ obtained by the C-V method.

The charge shapes for an irradiated ($\Phi_n > 10^{13} \text{ n/cm}^2$) detector at various bias at room temperature (RT) are shown in Fig. 3. It is clear that there are two components in the charge shape: a fast one that is associated with the drift current in the SCR (with a time constant τ_1) and a slow one for which the time constant τ_2 is related to the Maxwell relaxation time constant τ_m as the following [6,11]:

$$\tau_2 = \tau_m \cdot \frac{d}{w} \quad (4)$$

where

$$\tau_m = \frac{\epsilon \epsilon_0}{e \mu n(\text{or } p)} \quad (5)$$

We note here that for a given bias, τ_2 depends on the temperature T through n or p:

$$\tau_2 \propto \begin{cases} e^{-\frac{E_C - E_F}{kT}} & (\text{n-type}) \\ e^{-\frac{E_F - E_V}{kT}} & (\text{p-type}) \end{cases} \equiv e^{-\frac{E_F}{kT}} \quad (6)$$

It follows from Fig.3 that the amplitude of the fast component (the drift component) A_{dr} of the charge shape increases with the bias V before the full depletion, and saturates at the full depletion. In fact, A_{dr} is proportional to $V^{1/2}$ when $V < V_d$:

$$A_{dr} = \begin{cases} C\sqrt{V} & (V < V_d) \\ A_{dr}^{\max} & (V > V_d) \end{cases} \quad (7)$$

Fig. 4 shows the measured A_{dr} for the same detector shown in Fig. 3 as a function of $V^{1/2}$. The extrapolation of the linear part into the saturation gives the full depletion value $V_d = 110$ volts, which in turn gives the value of $N_{\text{eff}} = 1.60 \times 10^{12} \text{ /cm}^2$ using eq.(2) with $w = d$.

The charge shapes for the same detector shown in Fig.3 and 4, operated at a given bias at various temperatures are shown in Fig. 5. It is clear that the time constant of the slow component τ_2 decreases drastically with the temperature. Arrhenius plots of τ_2 for detectors irradiated to $3.2 \times 10^{13} \text{ n/cm}^2$ and

$5.89 \times 10^{14} \text{ n/cm}^2$ are shown in Fig. 6, which gives the Fermi level positions of $E_F = 0.483 \text{ eV}$ and $E_F = 0.498 \text{ eV}$, respectively. As shown in Fig. 7, the Fermi level is stabilized near the middle gap at all neutron fluences under study ($\Phi_n > 3.0 \times 10^{13} \text{ n/cm}^2$), similar to the findings in ref.[9]. The ENB resistivity was found also increasing with neutron fluence and tends to saturate at a value higher than the intrinsic value ($> 300 \text{ k}\Omega\text{-cm}$), in good agreement with ref. [6-8].

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Fig. 1 Laser induced current shape for a non-irradiated detector ($\Phi_n = 0.0 \text{ n/cm}^2$). The laser illumination was on the p^+ side of the detector.

Fig. 2 The time constant τ obtained from fitting the exponential decay of the current shape of a non-irradiated detector as a function of the detector bias.

Fig. 3 Charge shapes for an irradiated detector ($\Phi_n = 3.29 \times 10^{13} \text{ n/cm}^2$) at RT with different operating biases. Laser illumination was on the n^+ side of the detector.

Fig. 4 Amplitude of the fast component (A_{dr}) in the charge shape as a function of the square root of the bias for an irradiated detector ($\Phi_n = 3.29 \times 10^{13}$ n/cm²). A_{dr} saturates at the full depletion.

Fig. 6 Arrhenius plots of τ_2 for two detectors irradiated to different fluences.

Fig. 5 Charge shapes for an irradiated detector ($\Phi_n = 3.29 \times 10^{13}$ n/cm²) operated at a given bias at various temperatures. Laser illumination was on the n^+ side of the detector.

Fig. 7 Dependence of the Fermi level position on the neutron fluence.

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