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Capacitance simulation of irradiated semiconductor particle detectors(*)(**)

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Summary. — A simulation tool has been developed which allows the static calculation of the capacitance of a reverse biased diode. The influence of electrically active traps, coupled or uncoupled, on the C-V characteristic and the full depletion voltage of a diode can be studied. The simulations have been verified for a simple case where an analytical solution exists. A comparison of radiation measurements to calculations is shown.

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1. – Introduction

Semiconductor particle detectors can be degraded in a radiation environment. Evidence for this can be obtained by measurement of the capacitance and the bulk leakage current as a function of reverse bias voltage. The reason for the changes of these electrical characteristics is the generation of electrical active centers called traps. In this study we propose a versatile simulation tool which links the experimental observations to the trap density. It should enable the discrimination between effects arising from the behavior of the traps and the kinetics of defect formation.

2. – Numerical simulation

One-dimensional, stationary simulations of p^+nn^+ diodes have been performed. The basic semiconductor equations consisting of Poissson's equation and the two carrier continuity equations are solved self-consistently. Two coupled trap levels can be included. The

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simulations have been carried out with ZOMBIE [3], a one-dimensional general solver for nonlinear systems of coupled elliptic or parabolic differential equations.

2·1. *Net recombination rate and trap occupation probabilities.* – Two coupled defect levels are assumed which are characterized by the energies E_{t1} and E_{t2}, and the densities N_{t1} and N_{t2}. Each level can be either donor- or acceptor-like. The capture cross sections, $\sigma_{\nu j}$, are related to the carrier lifetimes by

$$\frac{1}{\tau_{\nu j}} = N_{tj} v_{\mathrm{th},\nu} \sigma_{\nu j}, \qquad \nu = n, p, \qquad j = 1, 2. \tag{1}$$

In the stationary case the net recombination rate due to two trap levels can be decomposed into

$$R = R^{(1)}_{\mathrm{SRH}} + R^{(2)}_{\mathrm{SRH}} + R^{(1,2)} \tag{2}$$

$R^{(j)}_{\mathrm{SRH}}$ denotes the Shockley-Read-Hall (SRH) rate for trap level j, while $R^{(1,2)}$ accounts for inter trap coupling.

$$R^{(j)}_{\mathrm{SRH}} = \frac{np - n_i^2}{\tau_{pj}(n + n_j) + \tau_{nj}(p + p_j)}, \tag{3}$$

$$n_j = n_i \exp\left[\frac{E_{tj} - E_i}{kT}\right], \qquad p_j = n_i \exp\left[\frac{E_i - E_{tj}}{kT}\right]. \tag{4}$$

Here, n_i and E_i refer to the intrinsic carrier density and the intrinsic Fermi level, respectively. The coupling term $R^{(1,2)}$, which is given by a more complex expression, is a function of the local carrier densities, n and p [4].

The Poisson equation has to account for the charge density carried by the traps. For acceptor-like traps we obtain

$$\mathrm{div}(\epsilon\, \mathrm{grad}\, \psi) = -e(N_{\mathrm{d}}^{+} - N_{\mathrm{a}}^{-} + p - n - f_{t1} N_{t1} - f_{t2} N_{t2}) \tag{5}$$

Following the work of Schenk [4], the stationary trap occupation probabilities, f_{t1} and f_{t2}, are functions of the local carrier densities.

2·2. *Static capacitance calculation.* – After solving the basic semiconductor equations at two reverse bias voltages, V_k and V_{k+1}, the positive- and negative-charge increments are computed by numerical integration.

$$\Delta Q_k^{+} = \int_0^d \Delta\rho_k(x) H(\Delta\rho_k(x))\mathrm{d}x, \qquad \Delta Q_k^{-} = \int_0^d \Delta\rho_k(x) H(-\Delta\rho_k(x))\mathrm{d}x, \tag{6}$$

$$\Delta\rho_k(x) = \rho_{k+1}(x) - \rho_k(x). \tag{7}$$

H denotes the unit step function. Because of global charge neutrality, $\int_0^d \rho(x)\mathrm{d}x = 0$, we have $\Delta Q_k^+ + \Delta Q_k^- = 0$. The capacitance at the voltage $V_{k+1/2} = (V_k + V_{k+1})/2$ is then obtained by a finite-difference expression

$$C_{k+1/2} = \frac{\Delta Q_k^+}{V_{k+1} - V_k}\,. \tag{8}$$

This method of calculation assumes that there is only one positive and one negative space charge region in the device, or, that the space charge density ρ changes its sign only once. If ρ changes its sign three times, which means that there are alternately two positive and two negative space charge regions, then (8) would be invalid. However, our simulations have never indicated the existence of more than one dipole region within the device.

3. – A simple analytical model

We can verify the simulations of the capacitance for a case which has a simple analytical solution.

3˙1. *Effective space charge density.* – For the analytical calculation we consider a constant donor doping, N_d, and one deep acceptor at the energy level E_t of density N_t both of which are uniformly distributed in the diode volume. If the reverse bias voltage is sufficiently big, $V \gg |E_\mathrm{t} - E_i|/e$, we can assume that the space charge density at the depletion edge x is simply given by $\rho = e(N_\mathrm{d} - f_\mathrm{t} N_\mathrm{t})$, where f_t is the occupation probability of the traps in the space charge region. Assuming a constant space charge density, integration of the Poisson equation yields

$$\mathrm{d}V = e|N_\mathrm{d} - f_\mathrm{t} N_\mathrm{t}| x \mathrm{d}x\,. \tag{9}$$

Since the capacitance C per unit surface is linked to the depletion width by

$$C = \frac{\epsilon_0 \epsilon_r}{x}\,, \tag{10}$$

where ϵ_r is the relative dielectric permittivity of the crystal, we obtain the following relation:

$$\frac{\mathrm{d}C^{-2}}{\mathrm{d}V} = \frac{2e|N_\mathrm{d} - f_\mathrm{t} N_\mathrm{t}|}{\epsilon_0 \epsilon_\mathrm{r}}\,, \tag{11}$$

which relates the C-V measurements to the effective charge density N_eff.

$$N_\mathrm{eff} = |N_\mathrm{d} - f_\mathrm{t} N_\mathrm{t}| \tag{12}$$

If we additionally assume that the occupation probability is governed by SRH statistics, we can calculate f_t as

$$f_\mathrm{t} = \frac{\tau_p n + \tau_n p_1}{\tau_p (n + n_1) + \tau_n (p + p_1)}\,. \tag{13}$$

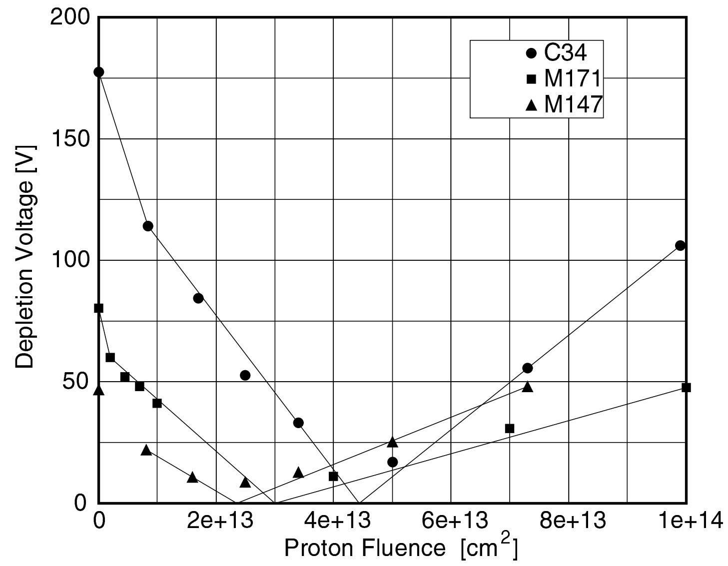

Fig. 1. – Measured depletion voltage as a function of the proton fluence for three different samples [1].

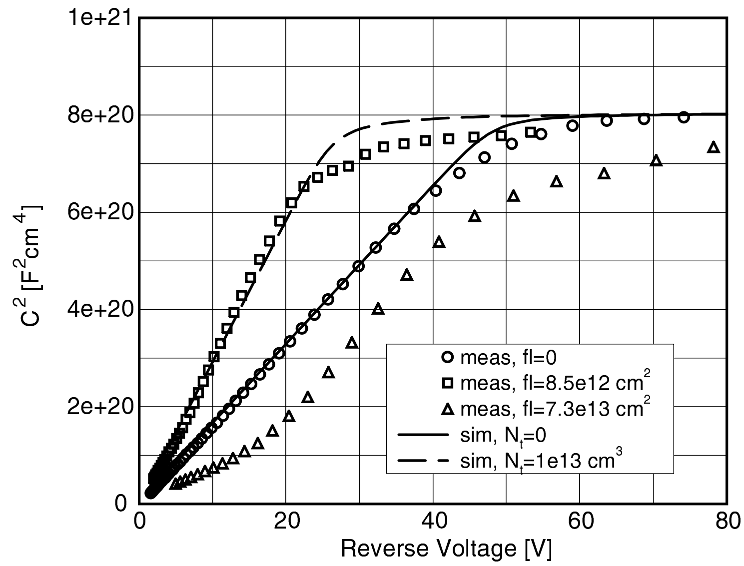

Fig. 2. – Comparison of measured and simulated C-V data for the sample M147. The parameters of the simulation are: $N_\mathrm{d} = 7.35 \cdot 10^{12}$ cm^{-3}, $d = 300$ μm, $E_\mathrm{t} = E_i + 50$ meV. To fit the slope of the sample irradiated with a fluence of fl$= 8.5 \cdot 10^{12}$ cm^{-3} a trap density of $N_\mathrm{t} = 10^{13}$ cm^{-3} was assumed.

Because the carrier densities are small in the depletion region ($n, p \ll n_i$), the occupation probability is constant and given by

$$f_{\mathrm{t}}^{\mathrm{dep}} = \left(1 + \frac{\tau_p}{\tau_n} \exp\left[\frac{2(E_{\mathrm{t}} - E_i)}{kT}\right]\right)^{-1} . \tag{14}$$

3˙2. *Discussion of analytical predictions.* – We can now compare (12) with N_{eff} determined from *C-V* measurements. If we assume that the introduction rate β of the traps is proportional to the fluence of the radiation, we can plot the measured depletion voltage, which is proportional to N_{eff}, as function of the fluence (fig. 1).

Two points can be deduced from (12). Firstly, $N_{\mathrm{eff}} = 0$, when

$$N_{\mathrm{t}} = N_{\mathrm{t}}^{*} \equiv \frac{N_{\mathrm{d}}}{f_{\mathrm{t}}^{\mathrm{dep}} \beta} \tag{15}$$

and, secondly, the slope of N_{eff} with respect N_{t} should be $-\beta f_{\mathrm{t}}^{\mathrm{dep}}$ for $N_{\mathrm{t}} < N_{\mathrm{t}}^{*}$ and $\beta f_{\mathrm{t}}^{\mathrm{dep}}$ for $N_{\mathrm{t}} > N_{\mathrm{t}}^{*}$

Having fitted straight lines to measured points (fig. 1) we notice that

a) the slope $|f_{\mathrm{t}}|$ beyond the fluence of inversion becomes systematically smaller and

b) at the onset of irradiation there is a pronounced change in slope.

The first observation indicates that the measurements cannot be explained by the action of one or more uncoupled trap levels which would always yield a linear dependence on fluence. Therefore, we conclude that either a second order process in the build-up of defects or a charge transfer between two coupled trap levels takes place. The second observation suggests that at the beginning of the irradiation electrons are removed to populate the deeper trap levels which are produced [2]. For the moment we were not able to reproduce this effect by simulation, even when two coupled trap levels are included.

Finally we have plotted the *C-V* measurements for the sample M147 [1] in a $1/C^2$ *vs.* V plot (fig. 2). We observe that the unirradiated sample follows a straight line as predicted by the relation (11) and confirmed by the simulation. The same is true for measurements up to moderate fluences of 10^{13} protons/cm^2.

However at high fluences the slope of the $1/C^2$ curve is no longer constant. We assume that this is due to a position-dependent trap distribution.

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