Modeling of Particle-Irradiated Devices

L. Colalongo, M. Valdinoci, M. Rudan

Dept. of Electronics, University of Bologna,
viale Risorgimento 2, 40136 Bologna, Italy

Abstract

Particle irradiation is largely used for controlling the carrier lifetimes in silicon power devices. In this paper a model is presented describing the effects of lifetime degradation due to particle irradiation, both in steady-state and transient conditions. By way of example, the model is applied to investigate the switching characteristics of an α-particle irradiated power diode.

1. Introduction

In recent years an increasing interest has been paid to lifetime engineering in semiconductor devices; specifically, weak fluxes of high-energy particles (α, protons, etc.) are used to control the carrier lifetimes in power semiconductor devices. The impinging particles create mechanical point defects, i.e., vacancies and self-interstitials. Such defects are created predominantly near the end of the particle range, which makes it possible to tailor the charge carrier lifetime at a certain depth in a device by modulating the particle energy. A typical application of this technique is in the field of power devices, where lifetime control is crucial due to the strict specifications imposed to their low-impedance, "on" state, and high-impedance, "off" state. Long carrier lifetimes and low resistivity are desirable during the "on" state to ease the current transport; on the other hand, when the device is switched off, the lifetime should be as low as possible to shorten the turn-off time. By using particles to lower the lifetime in a narrow region, the trade-off between such competing specifications can be improved substantially with respect to the other lifetime-controlling techniques, such as doping with gold or irradiation with high-energy electrons.
Here, generalizing the approach of [1], a model is presented describing the effects of lifetime degradation due to particle irradiation both in steady-state and transient conditions. To validate the developed model the switching of an α-particle irradiated power diode is shown here by way of example.

2. Model

High-energy particles impinging on silicon introduce a number of electronic states within the energy gap due to lattice damage. These states act as traps and recombination centers, and are characterized by the concentration, activation energy, and capture cross-section. The description of trapped-charge dynamics implemented in [1] can be generalized to an arbitrary number of independent acceptor and donor levels. To this purpose, it is necessary to redefine the generation-recombination rates for electrons and holes. If the number of independent energy levels is K, one finds, taking the electron net recombination rate by way of example,

$$U_n = \sum_{i=1}^{K} [\alpha_n(E_i) n N_i (1 - P(E_i)) - e_n(E_i) N_i P(E_i)] \,. \tag{1}$$

In (1), E_i is the energy of the ith trap-level, N_i its concentration, while $e_n(E_i)$, $\alpha_n(E_i)$ are the corresponding emission rate and capture coefficient; finally, $P(E_i)$ is the occupation probability of the ith level. A similar expression holds for the hole net recombination rate.

In the numerical solution for the transient case, the K trap levels give rise to K first-order differential equations for the occupation probabilities $P(E_1), \ldots, P(E_K)$. Such equations are coupled with those describing the charge transport within the conduction and valence bands; using the Backward-Euler solution scheme, their discretized form reads

$$P(E_i, t) = \frac{P(E_i)^{\text{old}} + [\alpha_n(E_i) n + e_p(E_i)]\Delta t}{1 + [\alpha_n(E_i) n + \alpha_p(E_i) p + e_n(E_i) + e_p(E_i)]\Delta t} \,, \tag{2}$$

where the label "old" stands for the quantity calculated and stored at the previous time step $t - \Delta t$.

The K probabilities (2) are used in (1) and in the definitions $n_t = \sum_{i=1}^{K} N_i P(E_i)$, $p_t = \sum_{i=1}^{K} N_i [1 - P(E_i)]$ of the trapped-carriers concentrations. In this way, the trap populations are accounted for in the system of semiconductor equations made of Poisson's equation and of the free-carriers continuity equations. In the former, the charge density accounts for carriers trapped within the acceptor (n_t) and donor (p_t) states, and reads $\rho = -q\,(p - n + N_D - N_A + p_t - n_t)$. In the continuity equations, the net recombination rates account for the trapped-carriers dynamics via (1) for electrons, and similarly for holes.

3. Application

An application example is shown with reference to an α-particle irradiated device. The parameters associated to the trap levels can be determined by DLTS measurements; in particular, the activation energies and capture cross-sections for the levels due to α-particle irradiation are reported in Tab. 1 [2].

Simulations have been carried out using HFIELDS [3] supplemented with the method described above. The turn-off of a p^+-n^- power diode with resistive-inductive load, before and after the damage induced by α-particle irradiation, is investigated. Such device, whose cross-section is shown in Fig. 1, is a typical workhorse to carry on experiments on the issue at hand [4, 5, 6]. The concentration profile of the defects used here is shown in Fig. 2.

The diode is biased with a 1 ns linear voltage ramp starting at $t = 0$ s, which brings the anodic voltage from 1 to -4 V. Fig. 3 shows the current flowing through the device vs. time, and Fig. 4 shows the corresponding anodic voltage. One sees that, as expected, in the case of α-particle irradiated devices, the storage time drops considerably. Simulations were also performed in order to evaluate the influence of the position of the peak concentration of the defects on the storage time, namely the time needed to form the space-charge region when switching from the forward to the off state. In this way the device performance can be optimized. Fig. 5 shows that the maximum efficiency of the irradiation process is reached when the peak is placed in the lightly-doped side of the space-charge region, right after the metallurgical junction.

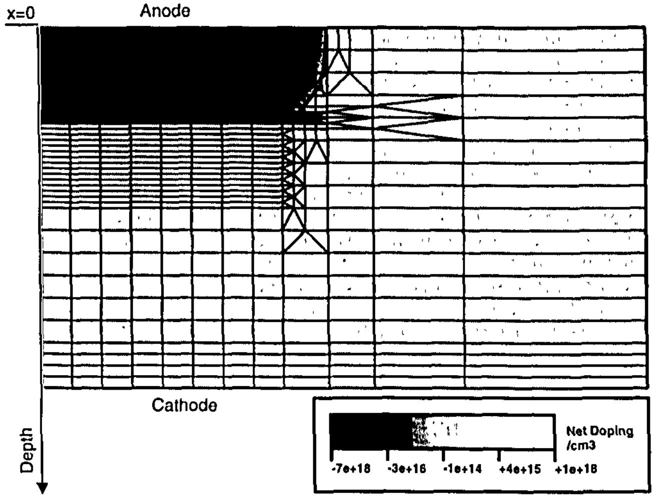

Fig. 1: Cross section of the simulated device. Doping distribution.

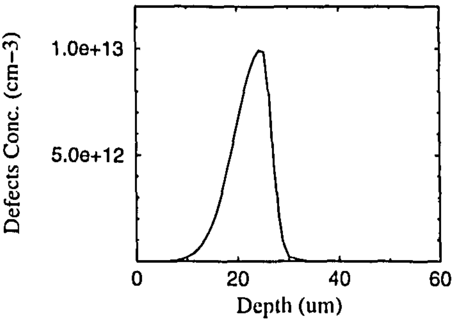

Fig. 2: Concentration profile of the defects.

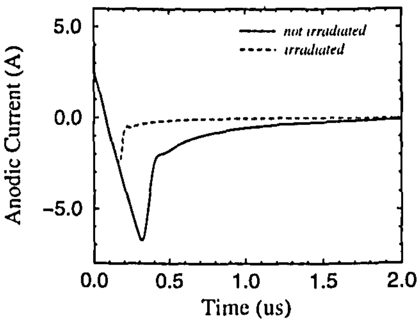

Fig. 3: Current flowing through the device. The diode is turned off with a 1 ns linear voltage ramp starting at $t = 0$ s. The dashed line corresponds to the α-irradiated device.

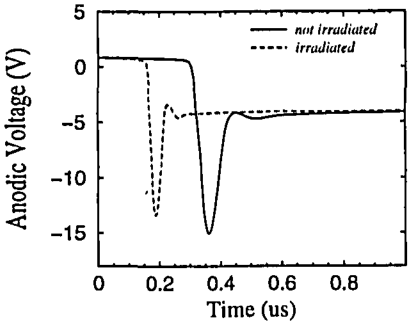

Fig. 4: Anodic voltage of the device during turn-off. The dashed line corresponds to the α-irradiated device.

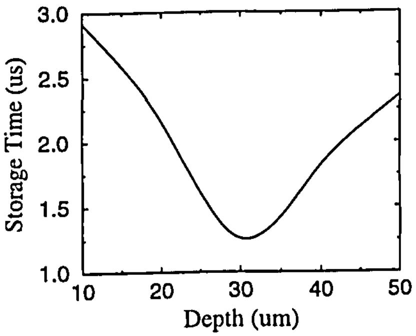

Fig. 5: Storage time vs. depth of irradiation.

TABLE 1

Level	Position (eV)	Capture cross-section (cm^2)
E_1	E_c-0.166	$\sigma_n = 2.3 \times 10^{-13}$
E_2	E_c-0.204	$\sigma_n = 2.2 \times 10^{-13}$
E_3	E_c-0.261	$\sigma_n = 1.7 \times 10^{-14}$
E_4	E_c-0.37	$\sigma_n = 1.4 \times 10^{-14}$
E_5	E_c-0.431	$\sigma_n = 3.4 \times 10^{-15}$
E_6	E_c-0.315	$\sigma_n = 1.1 \times 10^{-14}$
H_1	E_v+0.352	$\sigma_p = 3.1 \times 10^{-15}$
H_2	E_v+0.652	$\sigma_p = 1.0 \times 10^{-12}$

References

[1] L. Colalongo *et al.*, Proc. SISPAD 95, September 1995.

[2] N. Zafar, M. Zafar Iqbal, J. Appl. Phys., vol. 68, no. 2, 1990.

[3] G. Baccarani *et al.*, Proc. of the NASECODE IV Conference, Boole Press, 1985.

[4] A. Hallen *et al.*, J. Appl. Phys., vol. 67, no. 3, 1990.

[5] W. Wondrak *et al.*, J. Appl. Phys., vol. 62, no. 8, 1987

[6] M. Huppi, J. Appl. Phys., vol. 68, no. 6, 1990.