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Capacitance changes in neutron irradiated n-type silicon: The flux effect

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ABSTRACT

The influence of fast neutron flux on radiation-induced capacitance changes in heavily irradiated n-type Si has been studied by means of capacitance techniques. We have observed two regimes; flux-dependent and -independent for the case of high and low flux irradiation, respectively. A model that describes changes in the thermally stimulated capacitance as a function of time of irradiation has been proposed.

1. Introduction

Carrier removal due to irradiation by MeV electrons, protons and neutrons in semiconductors has been reported in numerous studies [1–4]. The observation of severe degradation of $n^+/p/p^+$ solar cell in the high radiation environment is caused by the introduction of radiation-induced recombination centers, which affect the carrier concentration and lead to the carrier removal [5,6]. The carrier removal can cause an increase of the series resistance and therefore affect devise properties [2].

The models which explain connection between the particle fluence and carrier concentration have been proposed [1,2]. However, the flux influence on radiation-induced changes is still an unresolved issue.

It is well known that interstitials (I) and vacancies (V), so-called primary radiation-induced defects, are created during the neutron irradiation. They either recombine, pair with impurities (e.g. O and P in n-type Si) or form clusters which can involve impurities. In that way secondary radiation-induced defects are formed. Small clusters may, however, directly form in the damage region by high energy neutrons, where a high density of primary I–V pairs is created [7]. All this damage has a major impact on devices, which rely on electrical properties like carrier concentration.

In this work, capacitance–voltage (*C*–*V*) and thermally stimulated capacitance (TSCAP) techniques were applied to investigate radiation-induced changes of the capacitance and carrier concentration in n-type Si. While the material was exposed to neutron irradiations at several levels of neutron flux, the same value of neutron fluence was accumulated in all cases in order to separate the flux effect.

2. Experimental details

The materials used in our experiment were phosphorus-doped Czohralski-grown (CZ) single silicon crystals with initial resistivity of 30 Ω cm. The $[O_i]$ in all the samples was about $1 \times 10^{18}\ cm^{-3}$. The samples were irradiated with 0.7 MeV neutrons in the carousel facility (CF) of the TRIGA Mark II reactor of the Jozef Stefan Institute in Ljubljana, Slovenia. Neutron irradiations were done inside a cadmium box with thickness of 1 mm to filter out the thermal neutrons. The effective cut-off energy of Cd is 0.55 eV, with distribution maximum for fast neutrons at 0.7 MeV [8]. The fluence of fast neutrons was $3.9 \times 10^{13}\ cm^{-2}$, and it has been achieved with various neutron flux, which has been varied from 8.1×10^9 through $1.3 \times 10^{11}\ n^\circ\ cm^{-2}\ s^{-1}$. The temperature of the samples during irradiation did not exceed 30 °C. Schottky diodes were fabricated by thermal evaporation of pure Au on surfaces etched in a $1HF + 10HNO_3$ acid mixture and rinsed in DI water. The samples were characterized with *C*–*V* and TSCAP techniques.

3. Results and discussion

Fig. 1 shows carrier concentration deduced from *C*–*V* profiles at 300 K as a function of fast neutron flux. As shown in Fig. 1, carrier concentration did not changed with different neutron flux.

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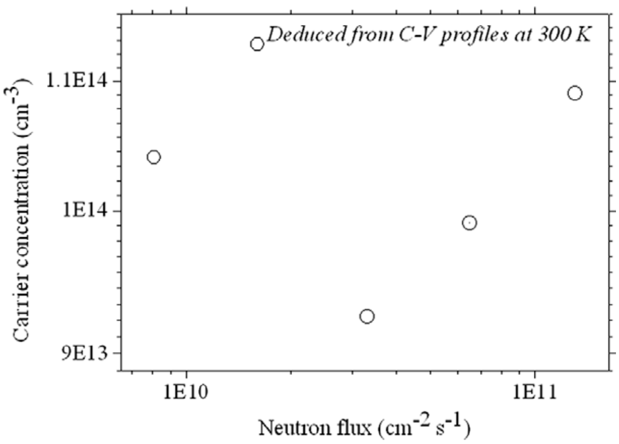

Fig. 1. Carrier concentration deduced from C–V profiles at 300 K as a function of neutron flux.

However, for the selected fluence (3.9×10^{13} cm^{-2}) the carrier removal has been detected. The initial carrier concentration was 2×10^{14} cm^{-3}, but upon irradiation obtained values for all samples were around 1×10^{14} cm^{-3}.

Using the following equation, we can estimate the carrier removal rate (K_n) [7]:

$$n(\phi) = n(0) - K_n\phi \qquad (1)$$

where $n(\phi)$ and $n(0)$ are the carrier concentration after and before exposure to a fluence ϕ, respectively. We have estimated the value of K_n as 2.6 cm^{-1}. This result is in good agreement with reported studies on fluence dependent carrier removal [7]. However, we shall go one step further and check the possible influence of flux on thermally stimulated capacitance by TSCAP technique.

Fig. 2 shows TSCAP spectra of the as irradiated samples for different neutron flux. Interesting feature in TSCAP has been observed, as we decreased the temperature, the TSCAP signal has gone to zero. This degradation of diodes i.e., increase of the resistivity is a consequence of the carrier removal, as observed with C–V. Moreover, we have observed that for the lowest neutron flux the capacitance drops to zero at the highest temperature ($T_{C\rightarrow 0}$ = 235 K), while for the highest flux the capacitance drops to zero at the lowest temperature ($T_{C\rightarrow 0}$ = 212 K). In this labeling T_C represents the temperature (K), deduced from TSCAP spectrum, at which the capacitance goes below 1 pF, e.g. for the lowest flux 8.1×10^9 n° cm^{-2} s^{-1} at T = 235 K the capacitance is 0.932 pF. Although, all our samples have received the same fluence of neutrons, the degradation of diodes is more pronounced for the lowest neutron flux, i.e., for the longest time of irradiation. Fig. 3 shows T_C deduced from TSCAP spectra as a function of time of irradiation. It should be noted that all changes are detected in a relatively small temperature interval. In order to obtain more experimental data, further experiments which would include more different values of neutron flux are needed. However, observed behavior clearly exhibits the exponential kinetics for the high flux, while T_C turns out to be a constant as we are decreasing the flux. As mentioned above, the literature data on flux dependence are extremely rare. Hono et al. [9] have reported the study on proton flux-dependent generation rates of radiation-induced defects in n-type Si. They have shown that generation rates for the VO (vacancy-oxygen center) and VV (divacancy) are flux-dependent. The dependence is given as following: the generation rate for the VO decreases as the flux increase, while the generation rate for the VV increases as the flux increase.

Moreover, Bergner et al. [10] have studied the flux dependence on cluster formation in neutron irradiated weld material. This study could not be directly linked with ours, as different material was used, but some general remarks could be taken. They show that the size of the irradiation induced clusters (vacancy-related) depend on the flux, as the flux is lowering the size of clusters is increasing [10].

Taking the all available information into account, we present a tentative model, which could correlate the degradation of diodes with the neutron flux i.e., with the time of irradiation. The temperature at which the capacitance of the irradiated diode goes to zero is exponential function of time of irradiation:

$$T_C(t) = T_{C_0}(1 - e^{-at}) \qquad (2)$$

where T_{C_0} and a are fitting parameters. As shown in Fig. 3 we can distinguish two different regimes, separate it with the "transition flux". In the case of low fluxes, steady-state, flux-independent regime is observed. However, the flux dependence on the generation rate of radiation-induced defects is dominant for the higher fluxes, and that defines the flux-dependent regime. We believe that at the highest fluxes when the time of irradiation is the lowest, the steady-state of primary radiation-induced defects is not reached. That affects the creation of secondary radiation-induced defects, as well. However, further studies with different levels of neutron flux are crucial for the verification of the model we have proposed.

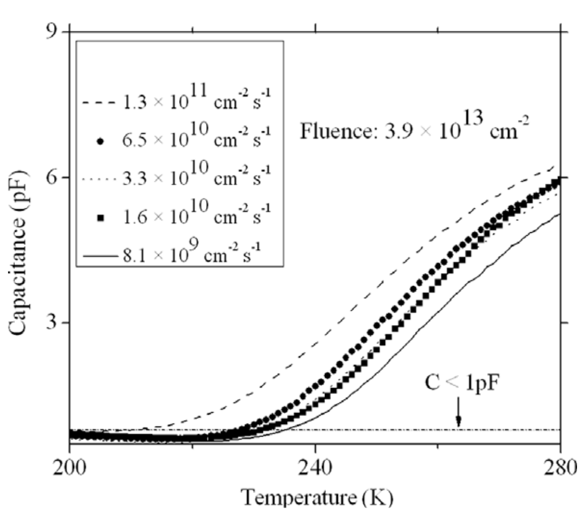

Fig. 2. TSCAP signal of n-type Si irradiated with different neutron flux. The dash-dot line indicates the region where the capacitance is below 1 pF.

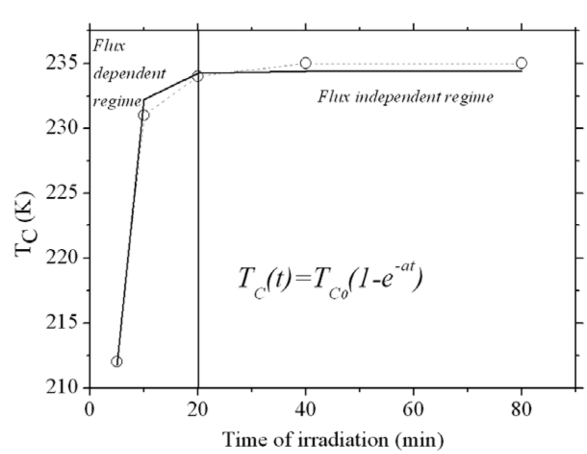

Fig. 3. Temperature T_C deduced from TSCAP spectra as a function of time of irradiation.

This result is valuable for understanding the degradation of devices used in radiation environment, such as solar cells and semiconductor detectors. Moreover, the observed flux dependence (Fig. 3) suggests that the lowest thermal budget is needed for the full (device) recovery when the highest flux is used.

4. Conclusions

In this work, we have demonstrated that although the carrier removal is not flux-dependent, the thermally stimulated capacitance is flux-dependent. The model which connects changes in the thermally stimulated capacitance with neutron flux has been proposed. Moreover, the flux-dependent and flux-independent regimes have been observed. Further experiments are needed for the complete verification of this model.

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