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Degradation of high-resistivity float zone and magnetic Czochralski n-type silicon detectors subjected to 2-MeV electron irradiation

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ABSTRACT

Particle-tracking detectors made on high-resistivity (HR) float zone (FZ) silicon are widely used in high-energy physics experiments. It is known that the incorporation of oxygen in the FZ Si can lead to some improvement in the radiation hardness of the material. In this contribution we investigate the effects of 2 MeV electron irradiation, up to a fluence of $5\times10^{16}\,e/cm^2$, on the electrical and carrier lifetime properties of p-on-n silicon diodes fabricated on different substrate materials, including HR standard and oxygenated FZ, as well as HR magnetic Czochralski silicon, with a higher intrinsic oxygen contents. A progressive degradation of the characteristics is observed for all devices, pointing to a generation of bulk damage. Interestingly, a significant increase of the effective carrier concentration is observed after the highest fluences for all materials. Under the limited experimental conditions studied, no significant changes are observed for diode characteristics subjected to a thermal annealing treatment at 80 °C. This degradation in the electrical properties should be taken into account for the use of such HR Si materials under high-energy electron environments.

1. Introduction

Particle-tracking detectors made on high-resistivity (HR) float zone (FZ) silicon are widely used in high-energy physics experiments. Results from the CERN RD48 [1] and RD50 [2] collaborations have shown that diffusion-oxygenated FZ (DOFZ) silicon can better withstand the high hadron fluences expected for 10-years operation of the Large Hadron Collider at CERN [1]. It is known that electron irradiation may also introduce significant bulk damage in silicon devices and this is of particular interest for certain environments like space applications or linear colliders. Type inversion after electron irradiation was first observed in p-type Czochralski (CZ) Si solar cells for space applications [3]. More recently, n-type to p-type conversion was also encountered after irradiation with ^{60}Co γ rays [4], which can produce low-energy electrons by Compton effect. Such type conversion after γ-rays was not observed in oxygen-rich DOFZ material [4]. The impact of high-energy electron irradiation on HR silicon for detector applications has been assessed in a series of recent publications [5–7], revealing the appearance of bulk-type inversion in either standard or oxygenated HR FZ, with no clear advantage in using DOFZ material.

Recently, new semiconductor industry interests and developments have enabled the production of magnetic Czochralski (MCZ) Si wafers with sufficient HR and with a well-controlled high concentration of interstitial oxygen ([O_i]). Although there are already some first-published studies assessing the radiation hardness of detectors fabricated on the new HR MCZ material, these have mostly concentrated on neutron, proton and γ irradiations [8,9]. The impact of electron irradiation on the new HR MCZ material remains still unclear as no type inversion has been observed and the first results point to either an effective dopant concentration lowering with 900 MeV e-irradiation [10] or just the opposite trend with γ-rays [9].

In order to shed some further light on the behavior of the HR MCZ n-type material under electron irradiation, silicon diodes including standard and oxygenated HR FZ as control materials were subjected to 2 MeV e-irradiations.

2. Experimental

The p-on-n diodes under study were manufactured at IMB-CNM following a well-established fabrication process [11,12].

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Table 1
Main specifications of the three HR Si substrates studied.

Substrate	HR MCZ	HR FZ	HR DOFZ
Supplier	Okmetic	Topsil	Topsil
Type	n	n	n
Orientation	⟨100⟩	⟨100⟩	⟨100⟩
Thickness (d) (μm)	300 ± 10	280 ± 15	280 ± 15
Resistivity (kΩ cm)	1.0 ± 0.1	4.5 ± 0.6	2.5 ± 0.1
Dopant conc. ($\times 10^{12}$ cm^{-3})	3.9 ± 0.4	0.9 ± 0.1	1.6 ± 0.1
Average [O$_i$] ($\times 10^{17}$ cm^{-3})	4.6 ± 0.2	< 0.09	1.7 ± 0.4

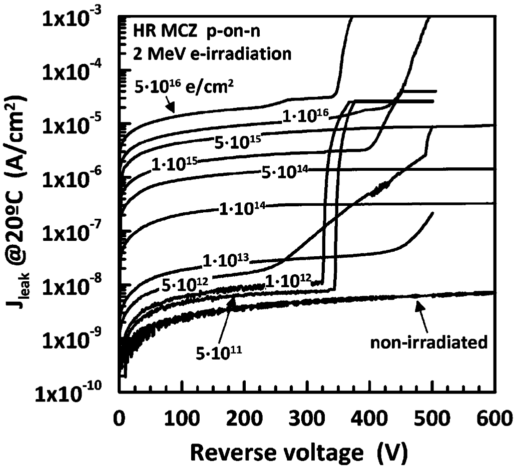

Fig. 1. J_{leak} versus voltage for irradiated HR MCZ detectors.

The starting material included HR FZ, DOFZ and MCZ Si wafers (Table 1). 2 MeV e-irradiations were performed at room temperature for different fluences (ϕ) between 5×10^{11} and 5×10^{16} e/cm^2 using the Dynamitron facility at Takasaki-JAERI, Japan.

Before and after irradiation, the electrical performance was evaluated by measuring the current–voltage (I_{leak}–V) and capacitance–voltage (C–V) characteristics. Exploratory minority carrier recombination lifetime (τ_r) measurements were performed by means of a microwave photo-conductance (μW-PCD) Semilab WT1000 setup [13].

3. Discussion

Fig. 1 shows typical radiation-induced degradation of leakage current density ($J_{\mathrm{leak}}\equiv I_{\mathrm{leak}}$/Area) for HR MCZ detectors. Similar results were obtained for their HR FZ and HR DOFZ counterparts. This points to a significant increase in the density of generation-recombination centers and bulk damage under electron irradiation. Interestingly, a significant degradation of capacitance versus voltage curves was also observed after the highest irradiation fluences (Fig. 2), showing an increase of the reverse bias voltage required to achieve full wafer thickness depletion (V_{FD}) [11], which is associated with an effective carrier concentration (N_{eff}) increase after the highest fluences (Figs. 3 and 4).

Regarding the leakage current increase (Fig. 1), as expected, a similar trend is observed for all the different materials ($I_{\mathrm{vol}} = \alpha\cdot\phi$, with $I_{\mathrm{vol}}\equiv J_{\mathrm{leak}}$/depth, with α values around 5.5×10^{-20} A/cm) (Fig. 5), in good agreement with those published in the literature for lower resistivity (standard) Si subjected to similar energy e-irradiations [14]. From α, an experimental estimation for the relative hardness factor of 2 MeV electrons with respect to 1 MeV neutrons gives a value of $\sim6.9\times10^{-4}$, which is significantly smaller than the estimated value (2.49×10^{-2}) obtained from the NIEL ratio [14,15]. The deviation from the NIEL scaling can be explained by a more pronounced introduction of point defects with respect to cluster formation under such energy e-irradiation [14,15].

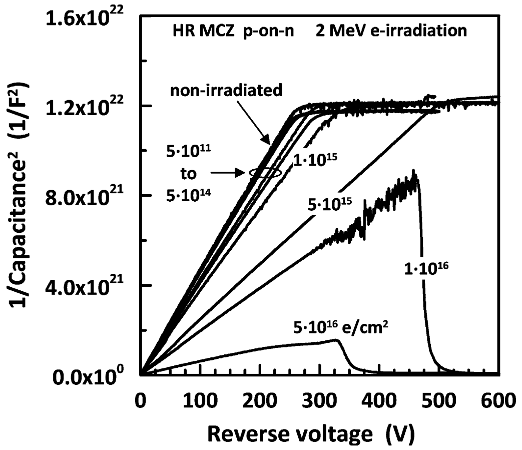

Fig. 2. $1/C^2$ versus reverse voltage for Fig. 1 detectors.

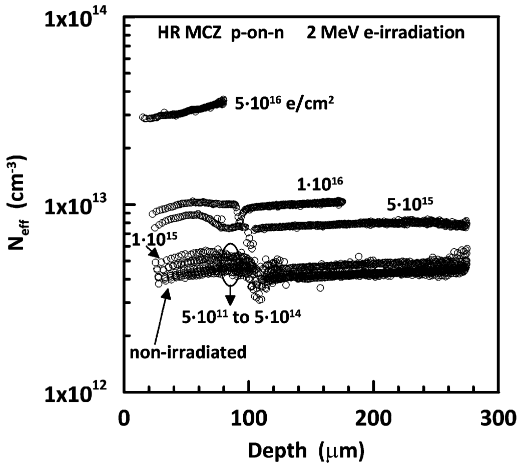

Fig. 3. Effective doping versus depth for Fig. 2 detectors.

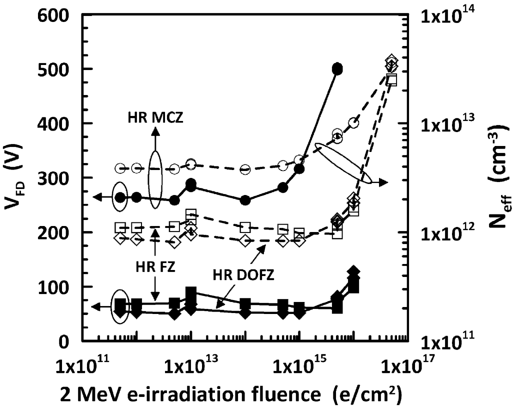

Fig. 4. V_{FD} and N_{eff} versus e-irradiation fluence for HR MCZ, HR FZ and HR DOFZ detectors.

Interestingly, the obtained μW-PCD τ_r values monotonically decrease with e-irradiation fluence (Fig. 5) and a certain correlation is found with the degradation of the generation lifetime (τ_g) extracted from J_{leak} versus depth plots (Figs. 6

and 7) [16]. By assuming a τ_g/τ_r ratio around 10 for low e-fluences ($\leqslant 1\times10^{15}$ e/cm^2), even a dominant effective trap level situated at about 60 mV from the intrinsic midgap position could be estimated.

Finally, in order to evaluate the thermal stability of the radiation-induced damage, a few irradiated diodes were subjected to thermal annealing treatments at 80 °C. Under the limited experimental conditions studied, no significant changes have been observed for the measured I–V and C–V characteristics (Figs. 8 and 9), and similar was the case even for the generation and recombination lifetimes.

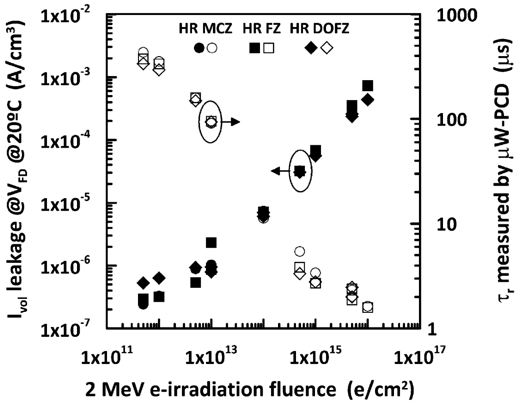

Fig. 5. Leakage current density ($I_{vol} = J_{leak}$/depth) and τ_r measured by μW-PCD as a function of e-irradiation fluence.

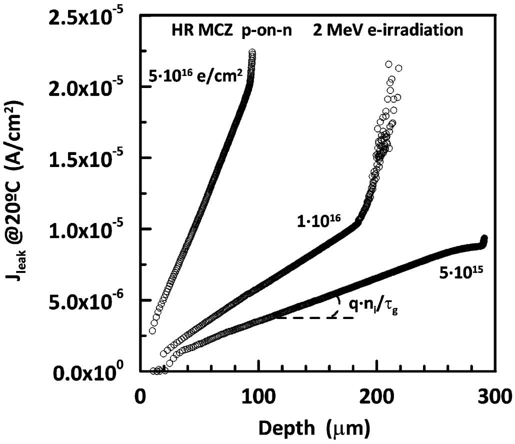

Fig. 6. J_{leak} versus depth for three irradiated HR MCZ detectors. τ_g is extracted from the slope of the linear region [16].

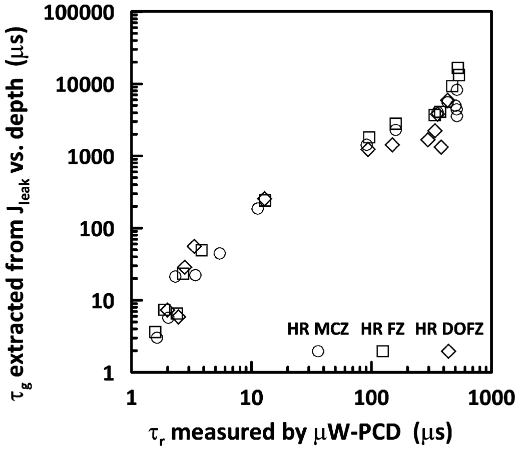

Fig. 7. τ_g versus τ_r for various irradiated and non-irradiated devices.

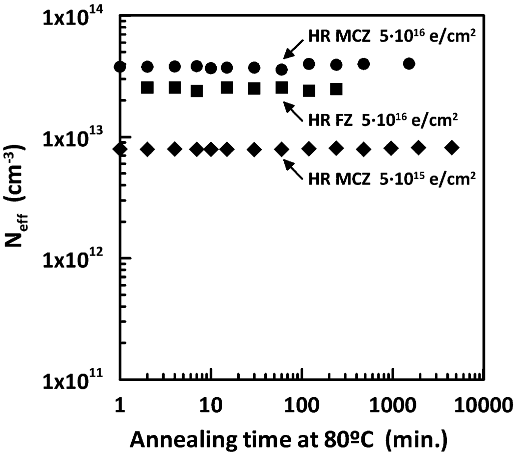

Fig. 8. N_{eff} as a function of annealing time at 80 °C for three different irradiated detectors.

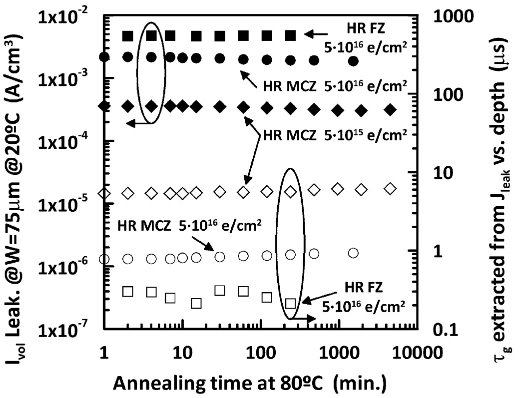

Fig. 9. Leakage current density ($I_{vol} = J_{leak}$/(at depth = 75 μm)) and τ_g as a function of annealing time at 80 °C for Fig. 8 devices.

4. Conclusions

A progressive degradation of the I–V curves is observed for all HR substrate diodes subjected to 2 MeV e-irradiation. Interestingly, a significant increase of the effective carrier concentration is also observed after the highest fluences for all materials. Under the experimental conditions studied, no impact of a thermal annealing treatment at 80 °C has been appreciated. This degradation in the electrical properties should be considered for the use of such HR Si materials under high-energy e-environments.

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