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8 MeV electron irradiation effects in silicon photo-detectors

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Abstract

Results of investigations on the electrical properties of n^+–p–p^+ silicon (Si) photo-detectors irradiated with 8 MeV electrons are presented. The photo-detectors were irradiated with electrons of doses up to 100 kGy. Current–voltage (*I–V*) and capacitance–voltage (*C–V*) characteristics under dark conditions were measured as a function of dose. A significant change in the diffusion component of the saturation current is observed after irradiation, while the generation-recombination component of the saturation current remains almost unchanged. The series resistance is found to increase with increasing dose while the shunt resistance and carrier concentration decrease with dose. Optoelectronic properties, namely short circuit current I_{sc}, open circuit voltage V_{oc} under air mass zero illumination and spectral response, were measured at various doses. From the spectral responses of the devices, the minority carrier diffusion length was estimated.
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1. Introduction

Semiconductor devices such as solar cells, photo-detectors etc. that need to be operated in space are often subjected to various types of radiation. Transient and permanent changes in the electrical properties of semiconductor devices induced by radiation may cause device degradation [1]. An understanding of the degradation mechanism is therefore necessary to improve the device performance under irradiation. n^+–p–p^+ Si photo-detectors used in this study have a device structure similar to Si solar cells. So studies of the radiation response and the defects responsible for the degradation of device performance of Si photo-detectors can also be useful for understanding the effects in Si solar cells. A photo-detector is an optoelectronic device that absorbs optical energy and converts it in to electrical energy, which is usually manifested as a photocurrent [2]. Si photo-detectors are used as sun sensors on board low-earth-orbit and geo-stationary satellites.

Though a vast amount of literature on radiation effects in Si based devices is available, most deal with the degradation in the opto-electronic properties of the devices. Studies on the effects of irradiation on the dark current and spectral response are sparse. Here the effect of 8 MeV electron irradiation on the electrical properties of Si photo-detectors over a range of doses is investigated.

2. Experimental

The n^+–p–p^+ silicon photo-detectors used here were fabricated by diffusion of phosphorous into p-type monocrystalline Czochralski (CZ) grown ⟨100⟩ oriented silicon wafers (doping concentration 10^{15} cm^{-3}) of resistivity close to 10 Ω cm. A p^+ rear surface layer was created on the back surface by depositing aluminium. A tri-layer metallic coating consisting of titanium, palladium and silver was

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deposited on a bus bar area within the n^+ diffusion region as well as the entire rear side using ion beam sputtering. A silicon oxy-nitride anti-reflection coating, tuned to a peak wavelength of 550 nm, was coated on the active area using ion beam sputtering. The dimensions and thickness of the photo-detectors is $5 \times 5\ \mathrm{mm}^2$ and 0.38 mm respectively.

Electron irradiation was performed at room temperature (25 °C) using 8 MeV electrons from a Microtron accelerator at various doses without any device bias. The devices were irradiated from the front surface. Irradiation was performed with a pulsed beam of average current 50 mA and duration 2.5 μs. The doses were measured using a Fricke dosimeter. The mean range of 8 MeV electrons in silicon is 0.39 cm. The irradiated devices were characterized soon after irradiation at room temperature. *I–V* characteristics were measured under dark conditions using a computer controlled Keithley 236 source/measure unit and *C–V* measurements at 1 MHz using a computer interfaced DLS-2000 system. The short circuit current under AM0 illumination was measured using a Spectrolab X/25 solar simulator and the spectral response using a Benthem spectro-radiometer, over the wavelength range of 400–1100 nm.

3. Results and discussion

Fig. 1(a) and (b) show plots of dark forward and reverse current versus voltage for a typical Si photo-detector at room temperature, before and after irradiation with 8 MeV electrons at various doses. Both the reverse and forward currents increase systematically with dose. The dark *I–V* characteristics of the device follow a double exponential law described by [3]

$$I = I_{01}\left[\exp\left(\frac{q(V - IR_s)}{n_1 kT}\right) - 1\right] + I_{02}\left[\exp\left(\frac{q(V - IR_s)}{n_2 kT}\right) - 1\right] + \frac{V - IR_s}{R_{sh}} \qquad (1)$$

where I_{01} and I_{02} are the saturation currents corresponding to the diffusion in the bulk and generation-recombination in the space charge region, 'n_1' and 'n_2' are the diode ideality factors, R_s and R_{sh} are the series and shunt resistances, k is the Boltzmann constant and T is the temperature.

The parameters, I_{01}, I_{02}, 'n_1', 'n_2', R_s and R_{sh} were evaluated from the dark forward *I–V* curves using Eq. (1) [4–6] and summarized in Table 1. A steady increase in I_{01} by about two orders of magnitude is observed with dose. The saturation current I_{02} is not affected significantly by irradiation. A small increase in the diode ideality factor 'n_1' of the device is observed after irradiation. 'n_2' seems to reduce up to a dose of 10 kGy after which it remains unchanged. There is an increase in the series resistance R_s with dose while the shunt resistance R_{sh} decreases with dose. Since I_{01} corresponds to the saturation current due to diffusion in the bulk material, the increase in I_{01} can be due to radiation-induced recombination centers in the base region of the device [3]. Electron irradiation might have produced recombination centers outside of the depletion region, primarily in the base region of the device, which lowers its minority carrier diffusion length. This is due to a change in the minority carrier lifetime. Since no

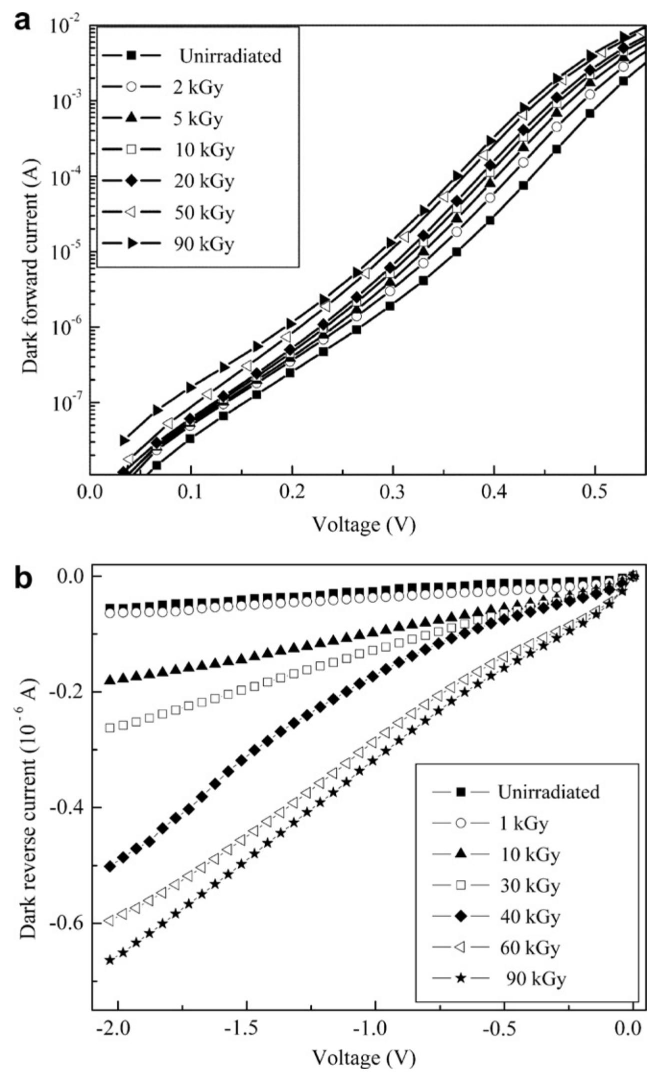

Fig. 1. (a) Semi logarithmic plot of dark forward *I–V* characteristics of an irradiated photo-detector at room temperature and (b) reverse *I–V* characteristics of an irradiated photo-detector at various doses.

Table 1
Diode parameters of Si photo-detectors as a function electron dose calculated from the dark forward *I–V* plot

Dose (kGy)	R_{sh} (MΩ)	R_s (Ω)	n_1	I_{01}(10^{-12} A)	n_2	I_{02} (10^{-9} A)
0	6.09	0.86	0.95	1.00	1.73	2.45
2	4.12	1.15	1.0	4.83	1.68	3.08
5	3.38	1.67	1.02	9.81	1.57	2.46
10	3.52	2.49	1.04	20.7	1.53	2.57
20	2.92	3.48	1.06	35.1	1.47	2.34
40	2.37	4.28	1.07	47.6	1.47	3.13
60	2.14	4.56	1.07	79.0	1.46	4.02
70	1.73	4.69	1.07	81.2	1.47	4.45
80	1.19	4.76	1.08	89.5	1.47	5.04
90	1.02	4.75	1.08	96.8	1.47	5.07

significant change in I_{02} is observed, this implies that there is no increase in the recombination centre density in the depletion region of the device. The recombination centers induced by electron irradiation might have influenced the series resistance, increasing it with dose.

To further characterize the junction properties, the capacitance of the device was measured as a function of junction voltage. Fig. 2 shows the dependence of $1/C^2$ on applied voltage of an electron irradiated Si photo-detector at room temperature. $1/C^2–V$ plots are linear for the samples before irradiation and remain so at all doses. This suggests that in all the samples, abrupt junction is not altered even after irradiation. The depletion layer capacitance, when a voltage V is applied to a junction is given by [7]

$$C = A\left[\frac{q\varepsilon_0\varepsilon_r N_A}{2(V_{bi}+V)}\right]^{1/2} \quad (2)$$

where A is the effective diode area, q is the electronic charge, N_A is the carrier concentration, ε_r is the dielectric constant of silicon, ε_0 is the vacuum permittivity, V_{bi} is the built-in potential.

N_A and V_{bi} can be estimated using Eq. (2). The total thickness of the depletion layer W of the junction can be given by [7]

$$W = \frac{\varepsilon_0\varepsilon_r A}{C} \quad (3)$$

The calculated depletion layer widths for the unirradiated sample are 0.72 μm at zero bias and 1.13 μm at −1 V bias. At 80 kGy, the depletion widths have increased to 0.74 μm at zero bias and 1.17 μm at −1 V bias.

Fig. 3 shows the variation of the carrier concentration, N_A with dose. A slight reduction in carrier concentration due to electron irradiation is observed. The diffusion potential remains the same for all doses so it can be concluded that no major change has taken place in the depletion region of the device. This indicates that most of the primary defects (vacancies and interstitials) produced by irradiation might have recombined before they can form stable complex defects, as the defects are very mobile at room temperature [8].

Fig. 4 shows the normalized solar cell parameters [open-circuit voltage (V_{oc}), short circuit current (I_{sc})] of n^+–p Si photo-detectors. The figure shows the cell parameter ratios compared to their initial values. The cell parameters show that V_{oc} degrades less compared to I_{sc}. This indicates that the damage occurs mostly in the base region of the cell [9].

Spectral responses of Si photo-detectors as a function of dose are shown in Fig. 5. Irradiation decreases the spectral response more in the longer wavelength region than in the shorter wavelength region. This indicates a decrease in the minority carrier diffusion length in the base region [9,10,12]. The minority carrier diffusion lengths of the devices before irradiation and at various doses of electron irradiation determined from the spectral response data [5] are shown in Fig. 6. The minority carrier diffusion length

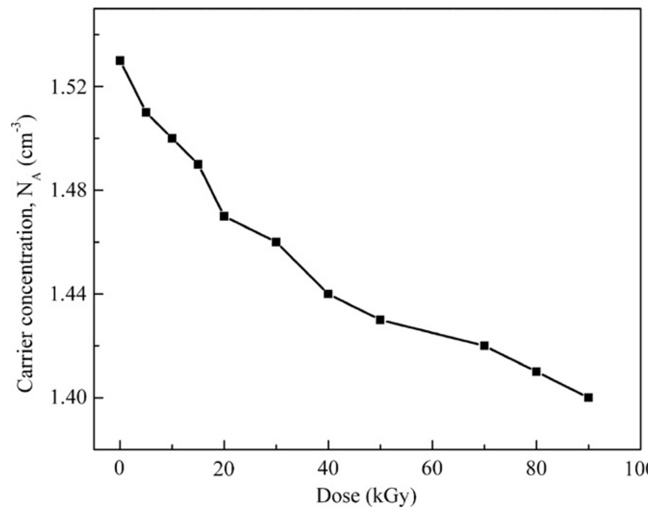

Fig. 3. Carrier concentration of the photo-detector as a function of dose.

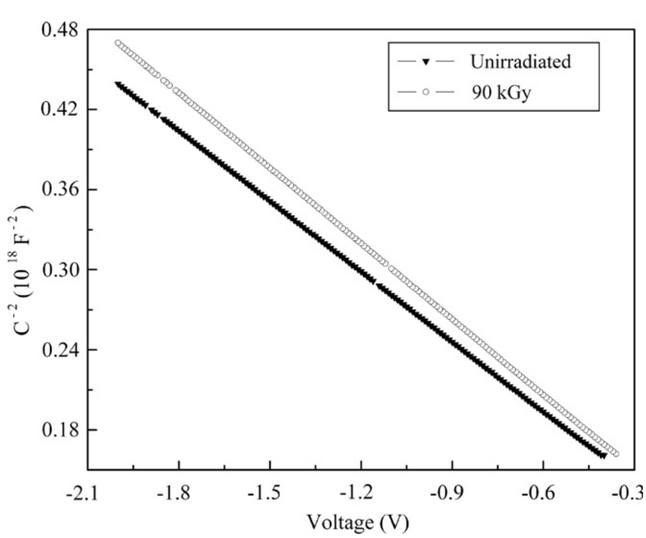

Fig. 2. Plot of $1/C^2$ versus V for an irradiated photo-detector.

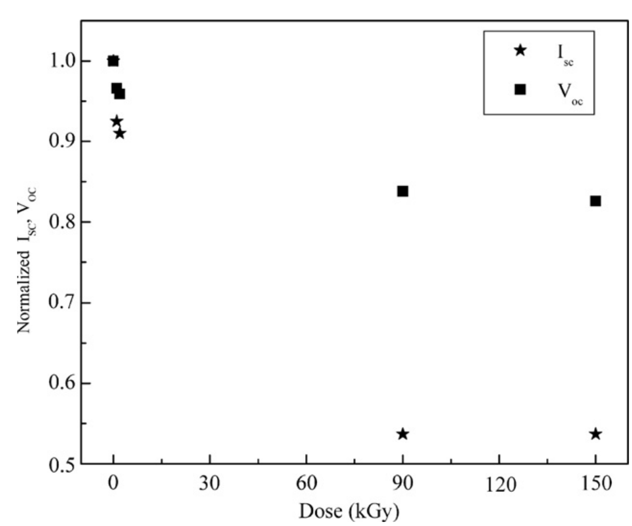

Fig. 4. Changes in normalized output parameters of photo-detector as a function of dose.

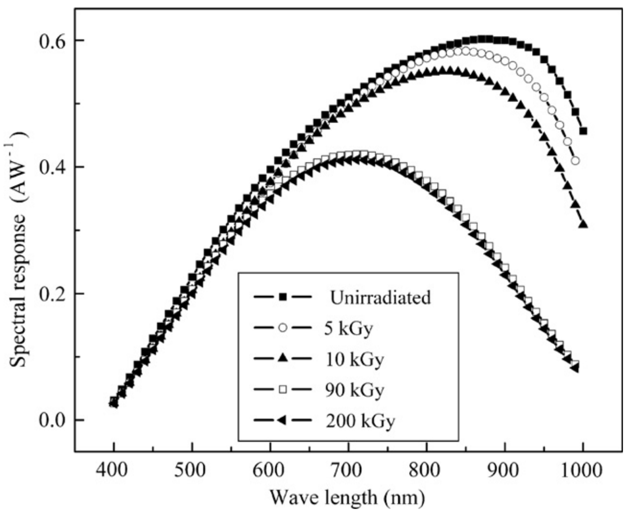

Fig. 5. Spectral response of photo-detector before and after irradiation with various doses.

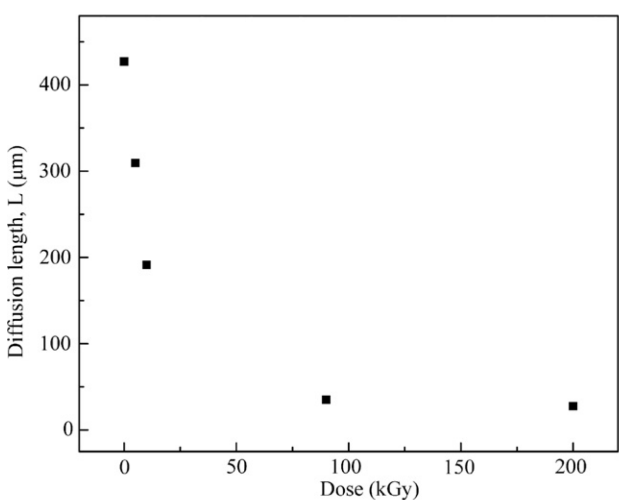

Fig. 6. Minority carrier diffusion length of photo-detectors as a function of dose.

markedly decreases with increasing electron dose up to 100 kGy, due to radiation-induced defects [1,11].

Radiation induced degradation in Si photo-detectors in the dose range studied is predominantly due to the generation of recombination centers in the base region, which decreases the minority carrier diffusion length ($L = \sqrt{D\tau}$). This results in an increase in the diffusion component of the saturation current. Electrons of MeV energies are capable of producing defects such as the A centre (vacancy-oxygen pair), divacancies and E centre (vacancy-phosphorous pair) in silicon [13–16]. These radiation induced defects are said to form recombination centers for minority carrier electrons which can cause degradation of the device.

4. Conclusions

From the study of electron irradiation effects on the electrical properties of n^+–p–p^+ silicon photo-detectors, the following conclusions can be drawn. The silicon device performance degrades with increasing electron dose. An analysis of I–V and C–V characteristics in the dark and spectral response, as a function of dose shows that irradiation introduces recombination centers in the base region of the device. This in turn causes degradation of the photo-detector performance due to the decrease of the minority carrier diffusion length.

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