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Studies on the temperature dependence of *I–V* and *C–V* characteristics of electron irradiated silicon photo-detectors

Manjunatha Pattabi[a,*], Sheeja Krishnan[a], Ganesh Sanjeev[b]

[a] *Department of Materials Science, Mangalore University, Mangalagangotri 574 199, India*
[b] *Microtron Centre, Mangalore University, Mangalagangotri 574 199, India*

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Abstract

The current transport mechanisms of n^+–p silicon (Si) photo-detectors in different temperature and bias regions before and after irradiation with a dose of 350 kGy has been investigated and presented in this article. Temperature-dependent dark current–voltage (*I–V*) studies under forward and reverse bias were carried out for this purpose. In the temperature range studied, the dark current contribution in the low bias range is believed to be due to the generation-recombination of minority carriers in the space-charge region. Electron irradiation does not seem to have altered the dark current conduction mechanism. Capacitance–voltage (*C–V*) at various temperatures was measured to identify the presence of deep levels in the device.

Keywords: Photo-detector; *I–V*; *C–V*; Current transport

1. Introduction

In any type of p–n junctions like solar cell, photo-detector etc., the dark current is detrimental to device performance and that is why it is very important to have the minimum possible value for the dark leakage current. Therefore, identification of the origin of dark current is essential to optimize the device performance [1,2]. The possible origins of dark current in p–n junctions are bulk diffusion, generation-recombination of minority carriers in the space-charge region, edge leakage [3–5], etc. Silicon (Si) photo-detectors are used in precision analog and digital sun sensors in a variety of configurations on board low Earth orbit and geo-stationary satellites and high-resolution radiometers [6]. Successful application of devices in advanced space-borne systems demand characterization of detector properties, like dark current under different ambient conditions and stability of the devices against adverse environmental conditions including radiation. In the present work, the various dark current mechanisms dominating n^+–p junction Si photo-detectors has been studied by measurements of *I–V* and *C–V* at different temperatures before and after irradiation with 8 MeV electrons at a dose of 350 kGy.

2. Experimental

The n^+–p Si photo-detectors used in the present study were fabricated by diffusion of phosphorous into the p-type monocrystalline silicon wafers of ⟨1 0 0⟩ orientation. A p^+ back surface field layer was created on the rear surface of the silicon wafer by depositing aluminum. As front and back ohmic contacts, metallic coating consisting of titanium, palladium and silver deposited using ion beam sputtering were used. Silicon oxy-nitride antireflection coating was made on the active area of the device using ion beam sputtering technique. Dark *I–V* characteristics of the samples were measured under both forward and reverse bias using a computer-controlled Keithley 236 source/measure unit. *C–V* measurements were carried out under dark conditions at 1 MHz using a computer interfaced DLS-2000 system. The samples were irradiated with 8 MeV electrons from a variable energy Microtron accelerator for various doses. The absorbed doses were measured using the

*Corresponding author. Tel.: +91 824 2287249; fax: +91 824 2287367.
E-mail address: manjupattabi@yahoo.com (M. Pattabi).

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Frickie dosimeter. The temperature-dependent dark *I–V* and *C–V* measurements of the samples were performed using a cryostat connected to the temperature controller unit of DLS-2000 system.

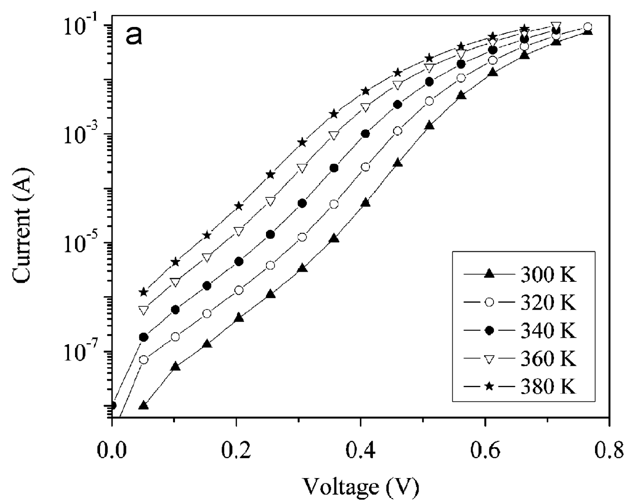
3. Results and discussion

3.1. Forward I–V characteristics

Figs. 1(a) and (b) shows the semi-logarithmic forward dark *I–V* plots at several temperatures for unirradiated Si photo-detectors and samples irradiated with electrons of dose 350 kGy, respectively. It can be seen that in both the figures, current increases exponentially with bias voltage. In the temperature range studied, two different slopes at low and high bias can be observed. *I–V* characteristics of a p–n junction can be described by the expression [3]

$$I = I_s \exp\left(\frac{qV}{nkT}\right), \tag{1}$$

where I_s is the device saturation current, '*n*' the ideality factor, *k* the Boltzmann constant and *T* the temperature.



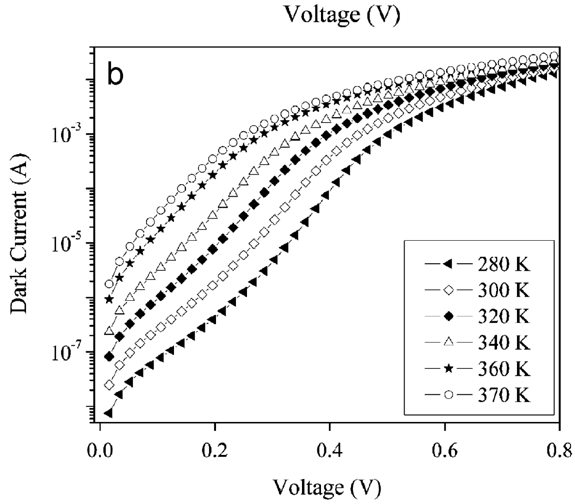


Fig. 1. Semi-logarithmic plot of forward *I–V* characteristics of Si photo-detector at various temperatures (a) unirradiated and (b) irradiated with electrons of dose 350 kGy.

The ideality factor is determined by the dominant current transport mechanism. '*n*' equals 2 when generation and recombination of electron–hole pairs in the junction depletion region dominates and '*n*' equals 1 when the diffusion current dominates [3,7].

The values of '*n*' and I_s are evaluated from *I–V* plots by fitting the data to Eq. (1) [3,7]. In order to identify the dominant dark current transport mechanism, the *I–V* characteristics were examined using various conduction models. The values of '*n*' lie between 1.89 at 300 K and 1.27 at 370 K before irradiation with corresponding values after irradiation being 1.84 and 1.41, respectively. The values of '*n*' lying between 1 and 2 suggest that the current is due to recombination within the depletion region [8]. A plot of $\ln(I_sT^{-2.5})$ versus $1/T$ is shown in Fig. 2. The activation energy determined from such a plot should be equal to approximately half the band gap if the current is controlled by the generation-recombination in the depletion region [9–12] and it should be close to the band gap if the current is controlled by diffusion [11,12]. The activation energy of the unirradiated and electron irradiated detectors calculated from the slope of the ln $(I_sT^{-2.5})$ versus $1/T$ plot is found to be 0.43 and 0.49 eV, respectively, close to half the band gap of Si. This suggests that the generation-recombination of carriers in the depletion region determines the dark current both before and after irradiation. The generation-recombination component of the current does not seem to change much after irradiation. Electron irradiation might not have caused major change in the depletion region of the device. Primary defects (vacancies and interstitials) are produced in this region. But it is possible that they are swept out of the charge depletion layer by the electric field before they have a chance of forming stable complex defects as they are very mobile at room temperature.

For applied voltages of over 0.4 V, the current is controlled by the diffusion of carriers. After 8 MeV

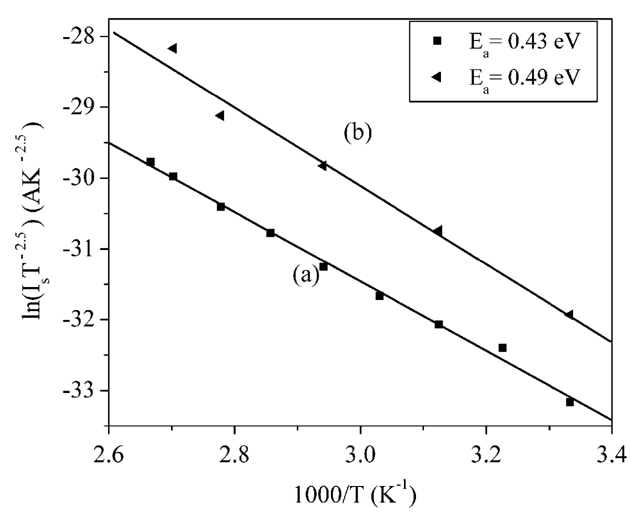
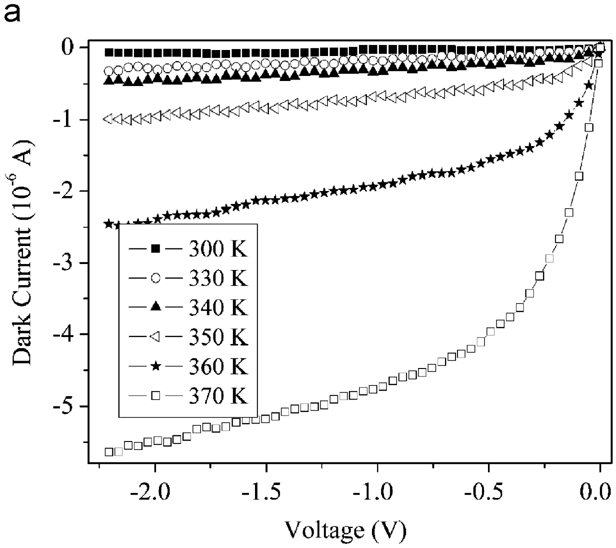


Fig. 2. Plot of $\ln(I_sT^{-2.5})$ vs. $1/T$ for the Si photo-detector in the dark temperatures (a) unirradiated and (b) irradiated with electrons of dose 350 kGy.

electron irradiation, a significant change was observed only for the diffusion component of the current. The increase in the diffusion current can be interpreted as resulting from a decrease of the minority carrier diffusion length in the base region. Recombination centers caused by electron irradiation might have been produced primarily in the base region of the device, which lowers the minority carrier diffusion length of the device [13].

3.2. Reverse I–V characteristics

Figs. 3(a) and (b) shows the reverse I–V characteristics of the unirradiated and electron irradiated photo-detectors at various temperatures. The reverse current does not show any saturation and is proportional to $V^{1/2}$ in the whole applied voltage range. This indicates that the dark current is governed by generation recombination of carriers in the depletion region. Fig. 4 shows the temperature dependence of the reverse current of unirradiated and electron irradiated Si photo-detector, plotted as $\log(I_R)$ as a function of $1000/T$. As the Arrhenius plot appears to exhibit a thermally activated behavior, the reverse current can be expressed as [14]



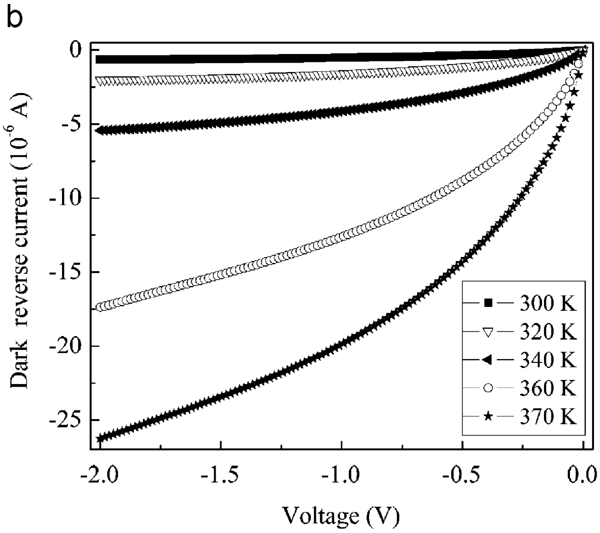


Fig. 3. A typical reverse current–voltage characteristics of Si photo-detector at various temperatures (a) unirradiated and (b) irradiated with electrons of dose 350 kGy.

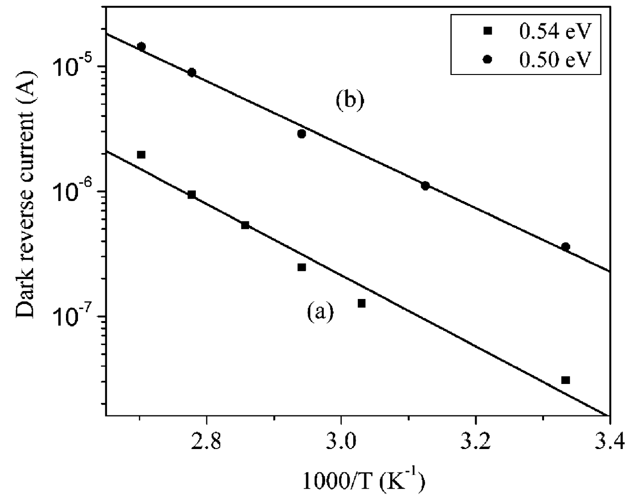


Fig. 4. Arrhenius plot of the reverse current of a Si photo-detector at a bias of −0.5 V (a) unirradiated and (b) irradiated with electrons of dose 350 kGy.

$$I_R(T) \propto \exp(-E_a/kT), \tag{2}$$

where E_a is the activation energy and k is the Boltzmann constant.

The activation energy calculated from the Arrhenius plot of the reverse current at −0.5 V are 0.54 and 0.5 eV for the unirradiated and irradiated photo-detectors, respectively. These values are close to $E_g/2$. This confirms that the reverse current is dominated by the carrier recombination in the depletion region in the temperature range studied [3,11].

3.3. Capacitance–voltage characteristics

The depletion layer capacitance of a junction at a voltage V is given by [3,14]

$$C = A\left[\frac{q\varepsilon_0\varepsilon_r N_D}{2(V_{bi}+V)}\right]^{1/2}, \tag{3}$$

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

Figs. 5(a) and (b) shows the dependence of $1/C^2$ on voltage at various temperatures. $1/C^2$–V plots are linear for the samples in the measured temperature range before and after irradiation. C–T variations at 1 MHz of the devices before and after irradiation are shown in Fig. 6. It can be seen that after irradiation, there is a slight deviation from linearity. All these indicate that considerable number of deep levels is not formed in the device even after irradiation [12].

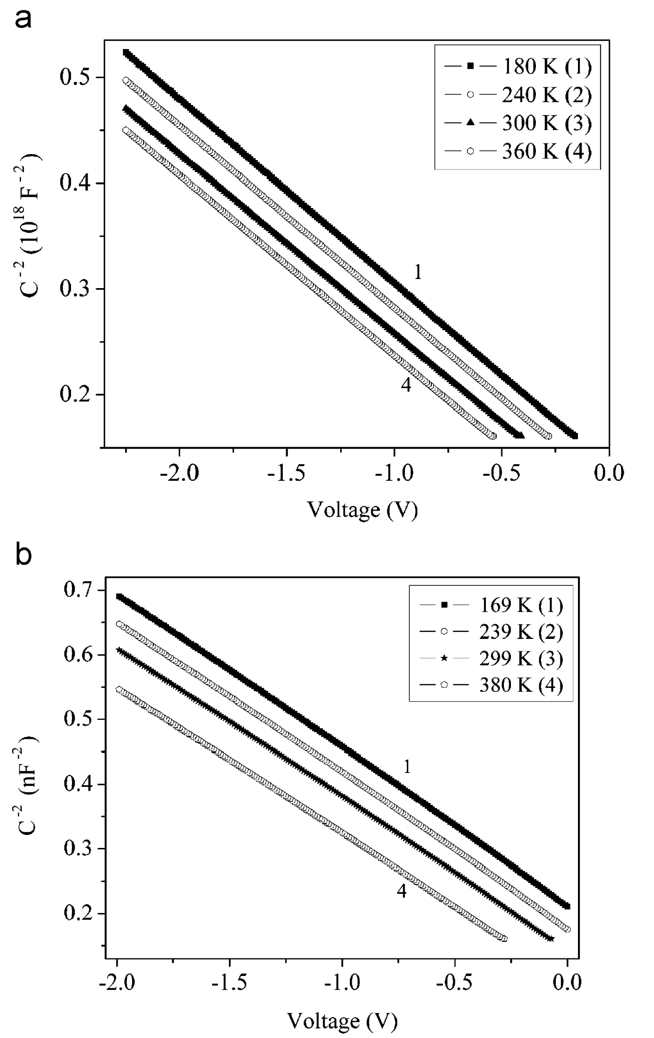


Fig. 5. Capacitance–voltage characteristics of Si photo-detector at various temperatures (a) unirradiated and (b) irradiated with electrons of dose 350 kGy.

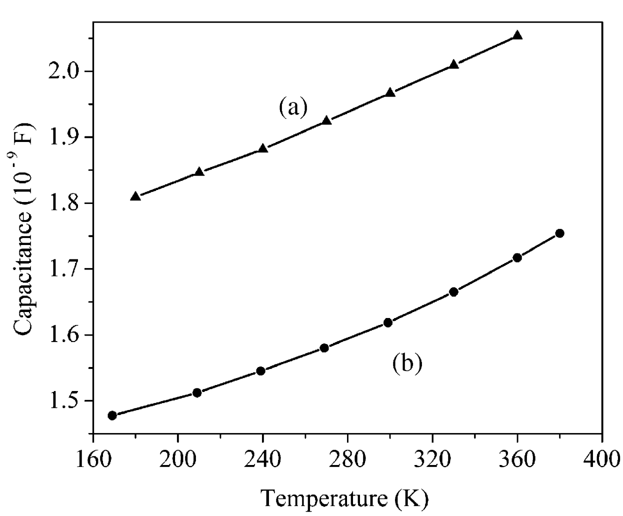


Fig. 6. Variation of capacitance with temperature of Si photo-detector (a) unirradiated and (b) irradiated with electrons of dose 350 kGy.

4. Conclusion

The dark current of n^+–p Si photo-detector was studied systematically as a function of applied bias voltage and temperature.

1. The dark current contribution at low bias, in the measured temperature range, is due to the generation-recombination of minority carriers in the depletion region.
2. Electron irradiation with a dose of 350 kGy does not seem to have changed the generation–recombination component of the dark current.
3. Electron irradiation might not have caused any major change in the depletion region of the device as generation recombination part of the dark current is not changed due to irradiation. But irradiation introduces recombination centers in the base region of the device, as indicated by the change in the diffusion component of the current, which decreases the minority carrier diffusion length.
4. Capacitance–voltage measurements indicate that considerable numbers of deep levels were not introduced by irradiation.

Acknowledgments

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