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Analysis of activation energy and conductivity in 1 MeV neutron irradiated silicon diodes

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ABSTRACT

In a highly 1 MeV neutron-irradiated silicon (Si) diode, an ohmic current-voltage (I-V) behaviour is observed, with the ohmic region increasing with radiation fluence. Reverse current (minority carrier density) increasing more drastically than forward current (majority carrier density) explains the conductivity-type inversion of material-based devices from *n*-to *p*-type after irradiation. The reverse current activation energy decreases from 0.86 eV for unirradiated Si diodes to 0.54 eV for the highest irradiated diodes, confirming the material conductivity-type inversion. The activation energy is independent of the radiation fluence just below the Si intrinsic Fermi energy, showing that when the defects near the centre of the Si band gap dominate the conduction mechanism, diode properties are independent of incident radiation. Despite its detrimental effects, radiation can improve the stability of diode properties. The stability of the properties is important for the fabrication of sensors for current and future high-energy physics experiments. The improved stability is because of radiation-induced defect levels close to the centre of the band gap that behave as generation-recombination (*g-r*) centres in Si.

1. Introduction

For a long time, researchers have been investigating radiation damage to silicon (Si) diodes [1–5]. The research is significant because diodes are employed as radiation sensors in high-energy physics experiments [2–5]. Because of their well-known technology, diodes have the potential for this application because defects can be introduced deliberately in Si to improve their properties [6,7]. In the coming years, the sensors are predicted to operate in radiation environments much harsher than the current ones [2]. As a result, it is important to improve sensor properties to meet the requirements for present and future challenges. The properties of heavily irradiated Si diodes, therefore, must be fully understood to fabricate radiation-hard sensors. In this context, radiation-hardness essentially means long-term efficiency.

The damage to the sensors is caused by radiation-induced defects in the material, resulting in a change in the electrical properties of the diodes. Defects are created because radiation imparts high-energy and momentum to the host atoms, to displace them from their lattice sites to create vacancies and interstitials in the material. The displaced atoms may interact with other atoms to create more defects in the materials as they come to rest. As a result, the crystal structure changes as defects are generated in the material. The induced defects are responsible for an increase in leakage current and full depletion voltage [8], resulting in a low radiation detection sensitivity of the diodes. Because of the incident radiation, the conductivity-type of the sensor changes from *n*-to *p*-type, showing either an increase in acceptor density or a decrease in donor density after irradiation [9]. All these changes result in a reduction in the charge collection efficiency of the sensor, making it unsuitable to be used in high-energy physics experiments.

An initial heavy irradiation improves the radiation-hardness of Si sensors [8,10]. Although radiation has detrimental effects, this favourable effect of radiation is because of radiation-induced defect levels at the centre of the Si band gap [7]. The density of these defect levels increases with radiation fluence, making the diode conduction mechanism dominated by generation (*g*) and recombination (*r*) centres. These defect levels pin the Fermi energy at the intrinsic position, making the properties of the material-based sensors independent of the incident radiation [11]. However, the electrical properties of the devices fabricated from the material with a high density of these defect levels are not fully understood since they are explained in terms of the controversial relaxation theory [7,8,12,13]. The relaxation theory employs parameters such as the dielectric relaxation time and the minority carrier recombination lifetime, which require sophisticated and expensive research equipment that is not readily available in most laboratories. Furthermore, most studies are conducted at room temperature, and the data does not adequately analyze the effects of radiation-induced defects

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on the diode's properties. It is therefore important that heavily irradiated Si sensors be analysed at different temperatures to understand the properties of radiation-induced defects. A full understanding of the defects would result in an improvement of their favourable properties and suppression of the unfavourable ones.

In this work, the effects of 1 MeV neutron radiation on the I-V properties of Si diodes at different temperatures are studied. The diodes are characterised to investigate a change in the diode's electrical characteristics as the fluence increases after the conductivity-type inversion fluence. 1 MeV neutrons are chosen in this study because they are more damaging particles deep in the material. A thorough understanding of the changes in diode properties caused by neutrons addresses challenges faced by sensors in other applications, not only in high-energy physics experiments, because we will understand the worst-case scenario. This

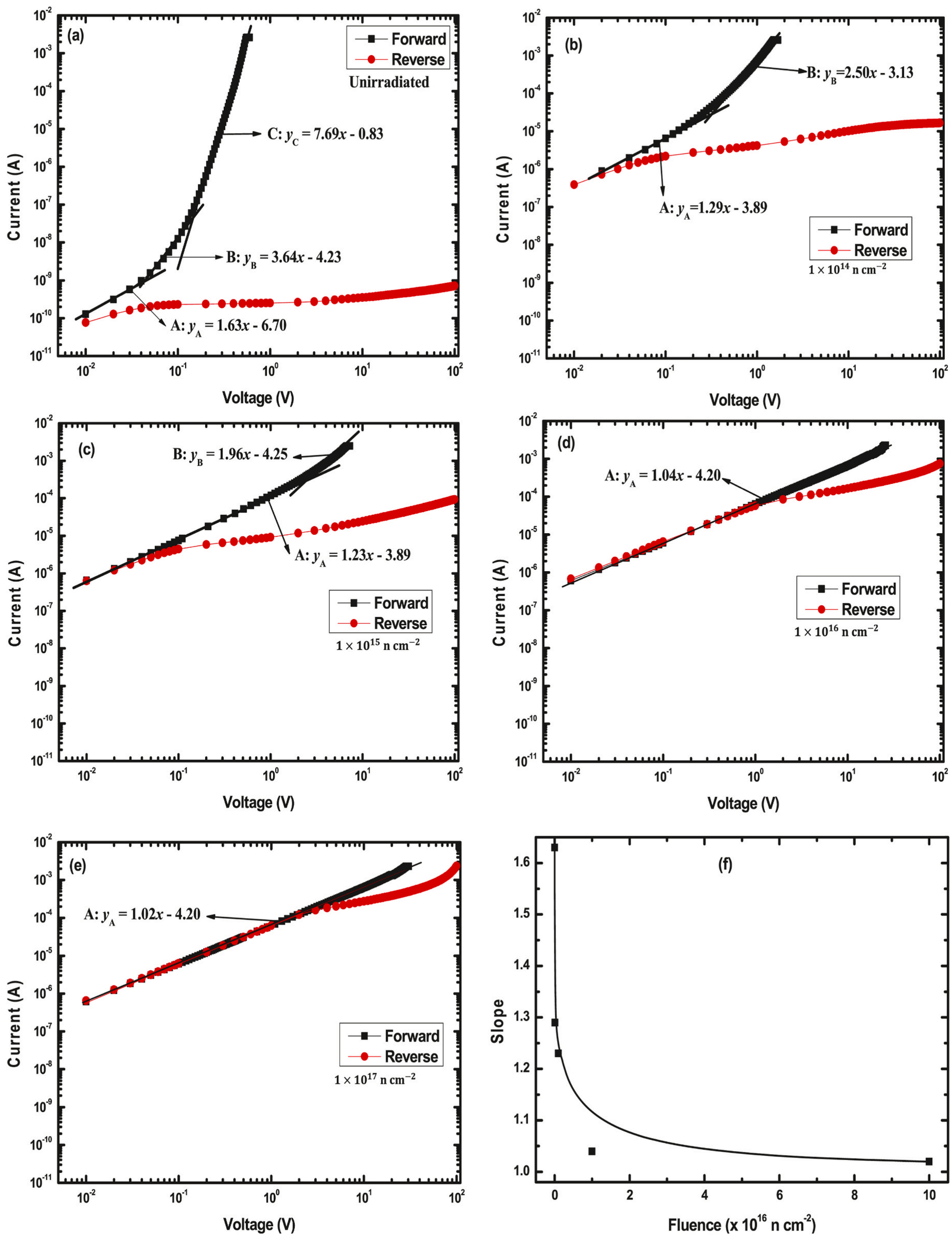

Fig. 1. I–V characteristics of unirradiated and 1 MeV neutron-irradiated diodes at various fluences (a-e) and the variation of slope with fluence at room temperature (f).

work is an addition to that presented based on the diodes irradiated up to 25 × 10^{13} n cm^{-2} [13], just after the material conductivity-type inversion [9]. The information presented in Ref. [13] is insufficient for the sensors to meet the requirements for the current and future high-energy physics experiments where they will be operated in a harsher radiation environment. As a result, studies on properties of diodes irradiated at much higher fluences worth investigation.

2. Experimental details

I-V measurements were carried out on unirradiated and irradiated samples at different temperatures using a meter made in-house. Samples in this work are Si *p-i-n* photodiodes acquired from industry [14]. The active diode area is 1 cm^2 and the thickness is 300 μm. Four diodes were irradiated at the National Energy Corporation of South Africa (NECSA) by 1 MeV neutrons to different fluences ranging from 10^{14} to 10^{17} n cm^{-2}, after the conductivity-type inversion fluence, ~1.4 × 10^{13} n cm^{-2} [9]. Similar experimental set-up used for AlGaAsSb-based devices [15] was adopted for our samples.

3. Results and discussion

Fig. 1 shows the *I–V* characteristics of the unirradiated, and the diodes irradiated with 1 MeV neutrons to the different fluences. The measurements were performed at room temperature to investigate a change in the diode's electrical properties with radiation fluence. At low voltages, the current increases with radiation fluence from ~ 10^{-10} A for unirradiated diode to 10^{-6} A for diode irradiated to 10^{17} n cm^{-2}. The current increases by the factor of 10^4 indicating that charge carrier density has increased after irradiation. However, at high voltages, forward current has decreased by a factor of 10^2, while reverse current has increased by a factor of 10^5. This change in the current indicates the generation of high-density minority carriers to compensate for the majority carrier resulting in an increase in the resistivity of the material. The compensation of the majority carriers is observed by the forward current trend changing from exponential to linear (ohmic) behaviour.

The diode's ohmic *I–V* behaviour indicates that the charge generation and recombination rates are equal ($g = r$) after irradiation. The observed increase in the ohmic region shows that the density of the radiation-induced defects responsible for this ohmic behaviour increases with radiation fluence. This ohmic diode behaviour is explained using relaxation theory [7,8,12] in terms of the defect levels positioned at the centre of the Si band gap. These defect levels interact with valence and conduction bands such that the Fermi energy of the material is pinned at the intrinsic position. When it is pinned at this position, the resistivity of Si is at its maximum, making the material suitable for the fabrication of radiation-hard detectors. The radiation-hardness of the detectors fabricated on the material with a high density of these defect levels has been presented before, and the device properties are independent of the incident radiation [8].

The slopes of linear regions observed in the forward current trends of Fig. 1 are used to investigate a change in diode conduction mechanism with radiation fluence. When the slope is 1, the dominant conduction mechanism is ohmic, while a slope of ~2 indicates that the conduction mechanism is dominated by space charge limited current (SCLC). The trapped charge limited current (TCLC) conduction mechanism dominates when the slope is greater than 2 [16]. Three linear regions with different slopes, A, B and C in Fig. 1(a) shows that there are three different conduction mechanisms involved in an unirradiated diode. The slopes are greater than 1 since the current and voltage are related by a quadratic relation, showing that the conduction mechanisms are dominated by SCLC and TCLC. A low slope in the first linear region (1.63) for this diode may indicate that the current is dominated by charge carriers generated by temperature in the low-voltage range.

The number of linear regions decreases, and only one linear region of the slope close to 1 is observed for the highest fluences in Fig. 1. Fig. 1 shows that radiation is responsible for the ohmic conduction mechanism, and this conduction mechanism dominates as the fluence increases. The ohmic conduction mechanism, as shown by a linear relationship between current and voltage, confirms that the charge generation rate (g) is equal to the recombination rate (r). In this situation where $g = r$, the reverse current and forward current trends are equal for the same voltages as observed in Fig. 1. Fig. 1 (e), however, shows that the trends are unequal at high voltages, possibly due to the slope not exactly being one (1.02). Fig. 1 (f) shows that after the diode has been irradiated to a certain fluence, very minimal change is observed in the slope of ln (I) vs. ln (V) curve even if the fluence increases. This shows that once the diode ohmic conduction mechanism dominates, the effect of radiation becomes negligible.

The stability of the diode properties after initial heavy radiation is confirmed by the variation of the rectification ratio (RR) (a ratio of forward current and reverse current at 0.5 V) with fluence in Fig. 2. RR decreases drastically at low fluences, indicating that the material gets damaged quickly at the initial radiation stage. A decrease in RR indicates the diode loses its rectification property because of the generation of minority carriers after irradiation [17]. Fig. 2, therefore, shows that the generation rate of the minority carriers is high at low radiation fluence as the material gets damaged by radiation. However, as the fluence increases, the RR becomes constant as the material becomes resistant to further radiation damage.

The *I–V* measurements in reverse bias carried out at different temperatures for all diodes are shown in Fig. 3. The current increases with temperature for the same voltage to show that charge carriers due to temperature contribute to the measured current. The striking observation from Fig. 3 is that the trends are close to each other, indicating that the current is relatively less dependent on the measurement temperature after irradiation. The diode current is less dependent on the measurement temperature due to the radiation-induced defects that are responsible for recombination of the thermally generated carriers to increase the resistivity of the material. This low temperature sensitivity of the diode shown in Fig. 3 indicates that the diodes are unsuitable for temperature sensing applications after irradiation. However, the insensitivity of the diode properties to temperature is very important for radiation sensing applications since the properties would be stable and, hence, the data acquired would be reliable when the diode heats-up during operation.

The reverse current (I) varies with temperature as

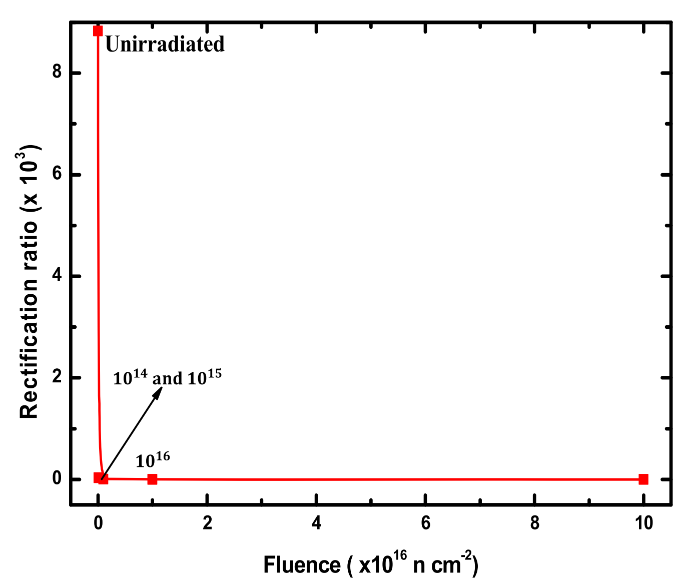

Fig. 2. A variation of rectification ratio evaluated at 0.5 V with radiation fluence at room temperature.

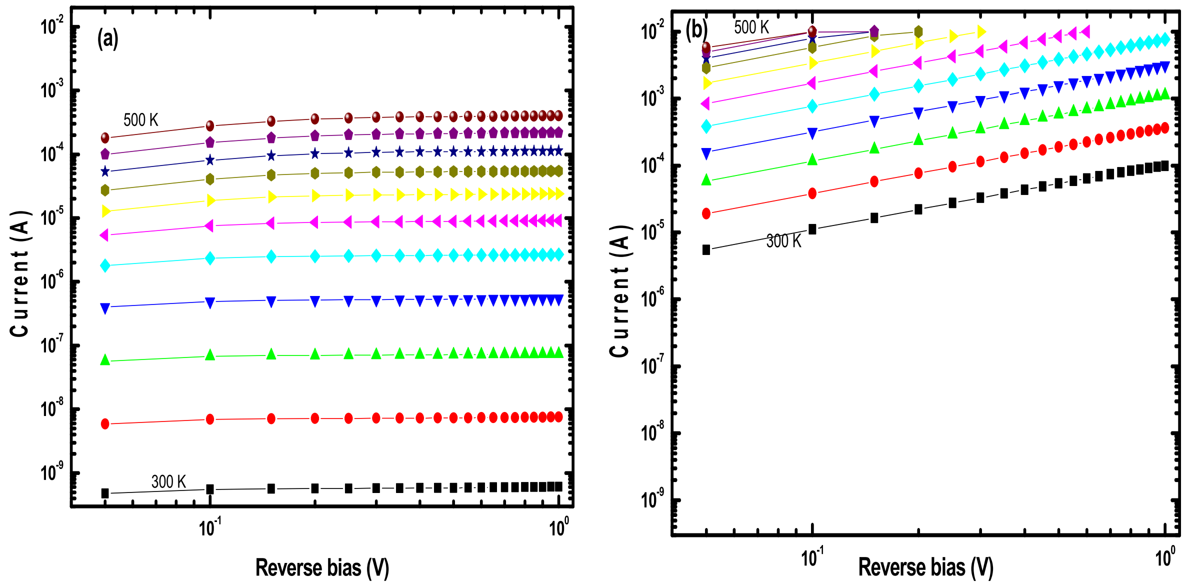

Fig. 3. A variation of the reverse I–V characteristics with temperature for the unirradiated diodes (a) and that irradiated to 10^{17} n cm^{-2}(b).

$$I \propto \exp\left(-\frac{E_a}{kT}\right) \tag{1}$$

where E_a is the diode activation energy. Eq. (1) shows that a plot of ln (I) against T^{-1} is a linear relation from which the slope is used to determine E_a. Fig. 4 shows the plots of ln (I) against T^{-1} for the unirradiated diode, and the diode irradiated to 10^{17} n cm^{-2} at 0.5 V. The linear relations found from both plots show that in reverse bias, one conduction mechanism dominates in this temperature range for each diode. The activation energies are evaluated as 0.86 eV and 0.54 eV, respectively.

The activation energy of the diodes as a function of the reverse voltage is shown in Fig. 5(a–e). Despite the jump at low voltages, Fig. 5 (a and d) shows that the activation energies for the unirradiated diode and that irradiated to 10^{16} n cm^{-2}, respectively, are independent of the bias, suggesting that the conduction mechanism is not dominated by electron trap. The activation energy of other diodes, on the other hand, is bias-dependent, indicating that the electric field enhances the electron emission from the trap. Fig. 5 (f) shows the activation energy of the irradiated diodes is found constantly in the lower half of the band gap, close to the intrinsic Fermi energy for all voltages.

Fig. 6 shows the activation energy evaluated at 0.5 V against the radiation fluence. The activation energy for the unirradiated diode is found in the upper half of the Si band gap, suggesting that the initial material could be an n-type conductivity. Thus, the independence of the activation energy from voltage (Fig. 5 (a)) for this diode is attributed to the donor levels. A decrease in the activation energy shows that radiation-induced defects have resulted in charge carrier traps in the band gap. The activation energy is in the lower half, indicating that the material conductivity is inverted to p-type conductivity due to radiation. A conductivity-type inversion could either be due to a drastic decrease in donor density by electron trap and/or the generation of minority carriers to compensate for majority carriers in Si.

The activation energy of the irradiated diodes is also close to the intrinsic Fermi energy. This shows that the conduction mechanism is dominated by defects positioned close to the centre of the band gap. At this position, these defects interact equally with both bands, such that

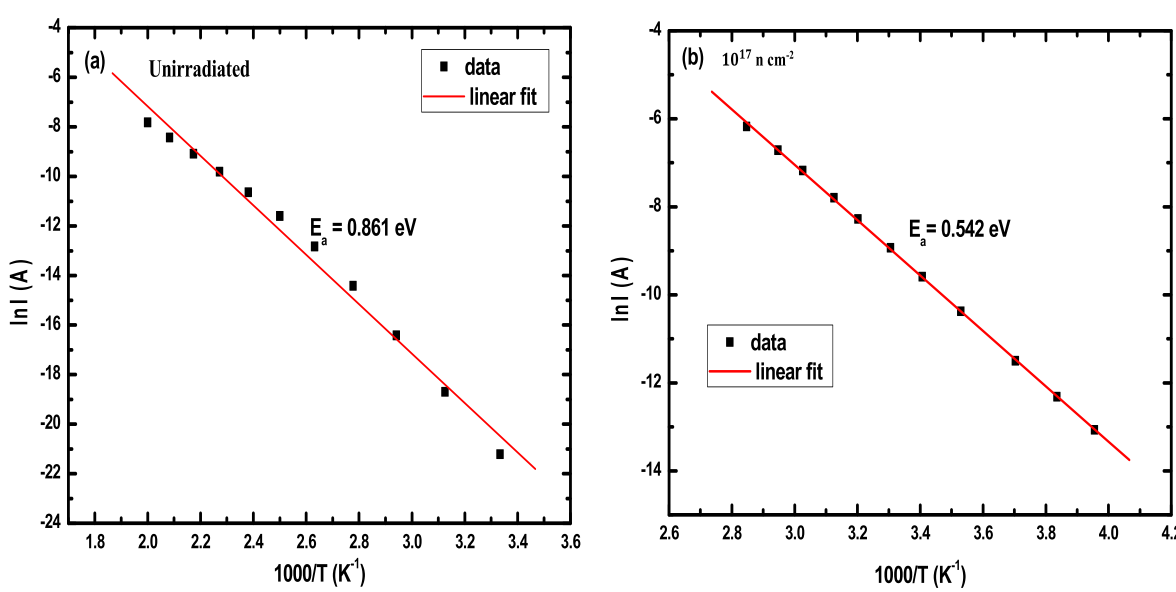

Fig. 4. The plots of ln (I) versus T^{-1} at a constant reverse bias of 0.5 V for the unirradiated diode (a) and the diode irradiated to 10^{17} n cm^{-2} (b).

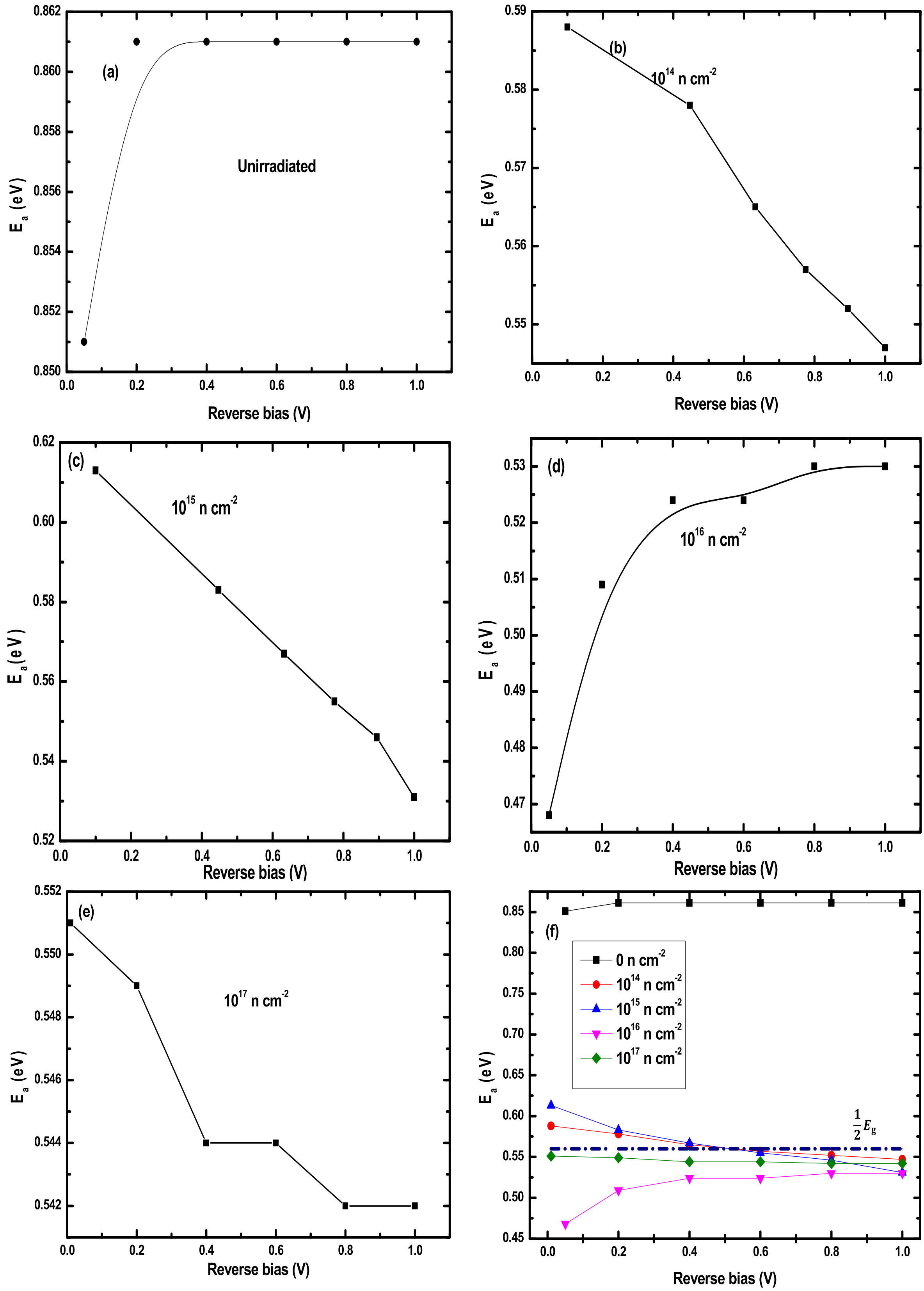

Fig. 5. The activation energy of the current for the unirradiated (a) and irradiated diodes (b-e) as a function of reverse voltage. The activation energy with respect to the intrinsic fermi energy as a function of the voltage ((f).

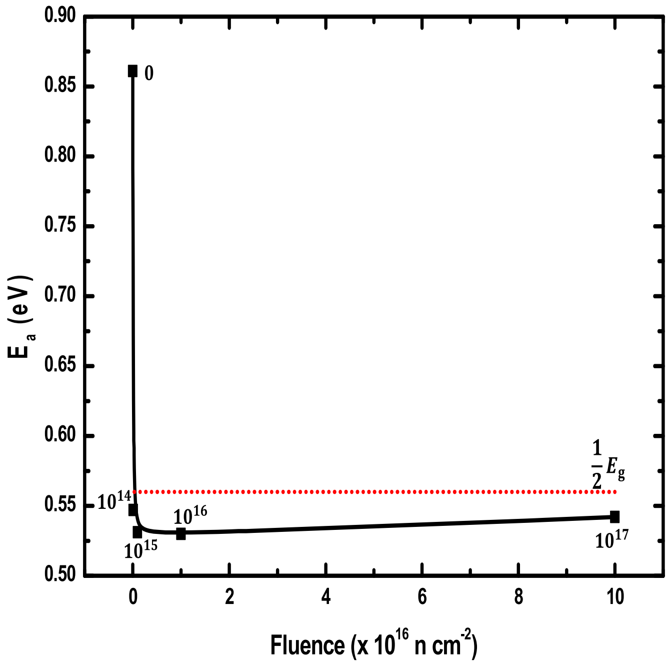

Fig. 6. The activation energy of the current for the unirradiated and irradiated diodes as a function of fluence with respect to the intrinsic fermi energy (red dotted line). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$g = r$. As a result of the rates being equal, the magnitudes of the reverse current and forward current are equal for the same voltage, as shown in Fig. 1. These defects are responsible for the drastic increase in leakage current because they produce a high density of minority carriers, which then recombine with majority carriers, creating an ohmic behaviour for the diode. For low radiation fluence the ohmic region is small because the density of defects responsible for ohmic behaviour is low [7,14]. In this work, however, the region of ohmic behaviour increases with fluence, indicating that radiation-induced defects close to the centre of the band gap increase with radiation fluence.

An increase in the diode leakage current indicates charge carrier generation activity for these defects. Since they are responsible for the compensation of electrons, the radiation-induced defects at the centre of the Si band gap have characteristics of electron traps, as shown by the dependence of the activation energy on voltage in Fig. 5 (b, c, and e). The recombination activity of the defects is confirmed by the independence of activation energy from voltage in Fig. 5 (d) for the diode irradiated to the fluence of 10^{16} n cm^{-2}. An increase in forward current at low voltages observed in Fig. 1 may indicate the recombination activity of radiation-induced defects in the band gap.

It is possible that radiation also induces defects which are responsible for either charge carrier generation resulting in an increase in conductivity or recombination resulting in a decrease in conductivity only. These results confirm that, besides those positioned at the centre, there are other radiation-induced defects positioned at different levels in the band gap. These defects, however, become relatively dormant as the density of those induced at the centre of the band gap increases. This inactivity of the defects responsible for the increase of forward current could be an indication that they anneal out with continued irradiation.

A drastic decrease of E_a at low fluences in Fig. 6 indicates a leap in material damage at the initial irradiation stage. However, as the fluence increases, E_a remains constant, indicating that the diode properties are radiation independent. The results presented in Fig. 6 show that when the density of the defects close to the centre of the band gap reaches a certain value, Si becomes resistant to further radiation damage. Because the Fermi energy is pinned at the intrinsic position and E_a is independent of radiation fluence, the material properties are independent of further incident radiation.

4. Conclusion

This work shows that the diodes irradiated with 1 MeV neutrons exhibit ohmic behaviour, with the ohmic region increasing with radiation fluence. As the diode becomes ohmic, the reverse current becomes less temperature dependent due to the recombination activity of the radiation-induced defects. A variation of E_a with fluence shows a change in the dominance of diode conduction mechanisms from the donor levels in the upper-half to the defects in the lower-half of the band gap. This change in the conduction mechanism to ohmic indicates the conductivity-type inversion of Si from *n*-to *p*-type. This conductivity-type inversion is because of an increase in the minority carrier density, as confirmed by the drastic increase in reverse current and decrease in RR due to irradiation. The independence of ohmic diode conduction mechanism and E_a close to the centre of the band gap indicates that diode properties are stable, and the conduction mechanisms are dominated by *g*-*r* centres close to the centre of the band after conductivity-type inversion radiation fluence. The stability of diode properties is the most important feature of detectors for efficient long-term operation in harsh radiation environments.

Author statement

S. J. Moloi: conceptualization, methodology, data analysis, writing-reviewing and editing.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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