Nuclear Inst. and Methods in Physics Research B 440 (2019) 64–67

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Reverse annealing studies of irradiated silicon by use of current–voltage measurements

S.J. Moloi[a,*], M. McPherson[b]

[a] Department of Physics, University of South Africa, Private Bag X 6, Florida 1710, South Africa
[b] Centre for Postgraduate Studies, Cape Peninsula University of Technology, P.O. Box 652, Cape Town 8000, South Africa

ARTICLE INFO

Keywords:
Semiconductor
Silicon
Diode
Current
Radiation
Annealing

ABSTRACT

The annealing behaviour of irradiated silicon *p-i-n* diodes has been investigated by use of *I–V* measurements. The radiation-induced damage is achieved by the use of 1 MeV neutrons. The results have been analysed and a striking feature is easily noticeable where defects that do not anneal out alter their activity and behave more as generation centres. This means that they are situated in the upper half of the band gap where they act to increase the carrier density and the measured current. The increase in current starts to occur at around 100 days and a change in trap activity at around 180 days after irradiation. The device behaviour, however, remains ohmic throughout indicating that a defect level that is responsible for relaxation behaviour is stable. This study would assist in demonstrating stability of silicon radiation detectors during their operational time.

1. Introduction

In an attempt to improve radiation-hardness of silicon, properties of radiation-induced defects are studied by current–voltage (*I–V*) technique [1–4]. Studies on the induced defects are necessary since devices fabricated on silicon suffer radiation damage when they are used as radiation detectors [5]. The damage is induced when high energetic particles impart momentum to the lattice of silicon such that atomic displacements occur. This culminates in the generation of a large number of intrinsic point defects that have levels within the energy gap of silicon. Further to this, the radiation removes shallow impurity levels by creating defect complexes [6]. The damage also introduces deep donors and acceptors into the energy gap and these compensate shallow acceptors and donors, respectively, to increase the resistivity of the material [7].

The induced defects are responsible for change in electrical properties of the devices, hence, in instability when they are used as radiation detectors [8]. In the particular case of radiation damage by 1 MeV neutrons, the generation–recombination (g–r) centres are created in the semiconductor [9]. These centres are situated in the middle of the band gap where they interact equally with either band [10] such that they equally generate or recombine charge carriers. They maintain carrier densities at intrinsic levels to make the semiconductor semi-insulating [11]. The effects of these centres are noticed by ohmic behaviour of the devices after radiation damage [12].

Though a study on radiation damage in silicon has been carried out for so long, properties of the induced defects have not been fully understood [13–16]. A change in properties of the induced defects with time after irradiation has not been thoroughly investigated [17]. It also has to be noted that a reason for reverse annealing on the type-inverted devices in contrast to other devices has not been provided [18]. It was assumed that the reverse annealing is due to the transformation of originally inactive defects into acceptor-like states [13]. This would imply that inactive defects would recombine the generated carriers to reduce the conductivity of the material. It has been shown in this work that this is not the case. The reduction of the conductivity occurs for few days after the damage and then increases.

In this work the possible annealing effects of the irradiated silicon devices were investigated using *I–V* measurements. The device under the test was irradiated by 1 MeV neutrons to a fluence of 1×10^{14} n-cm^{-2}, just after type inversion [19]. The results show that the device has attained relaxation behaviour [9] and repairs itself such that the current decreases initially. The current then increases after 100 days showing that defect(s) that does not anneal out acts as generation centres to increase the conductivity. The defects responsible for relaxation behaviour are, however, stable for 250 days. This study will lead to a clear explanation of a change in properties of the induced defects with time after irradiation.

* Corresponding author.
E-mail addresses: moloisj@unisa.ac.za (S.J. Moloi), McPhersonM@cput.ac.za (M. McPherson).

https://doi.org/10.1016/j.nimb.2018.11.025
Received 17 July 2018; Received in revised form 13 November 2018; Accepted 13 November 2018
Available online 04 December 2018
0168-583X/

2. Experimental details

The sample under investigation in this work is a commercial silicon *p-i-n* photodiodes fabricated from high purity, high resistivity silicon. The photodiode was acquired from Hamamatsu with the series number of S3590-08 [20]. The active diode area is 1 cm^2 and the thickness is 300 µm. The diode was irradiated by 1 MeV neutrons to a fluence of 10^{14} n-cm^{-2} at National Energy Cooperation of South Africa.

Prior to irradiation, *I–V* measurements were taken at room temperature, 300 ± 2 K, with the diode placed in the dark. These measurements were carried out on the sample using Keithley 6487 picoammeter with a voltage source. The instrument was operated in the remote (REM) mode by connecting it to a personal computer (PC) through an RS-232 cable. An add-in utility for Microsoft Excel was installed in the PC for control of the picoammeter and for data acquisition. The measurements were taken in three voltage steps of 0.01 V up to 0.1 V, of 0.1 up to 1 V and finally of 1 V up to the maximum voltage, 100 V, to be applied to the device in reverse bias as quoted by manufacturer. In forward bias, the measurements were taken in steps of 0.01 V up to the imposed current limit. In all the experiments the current was set to 2.5 mA. In either bias condition the time between measurements was set at 1 s to allow the current to settle (or the device to stabilize). After irradiation, the same measurements were performed under similar conditions to establish a change in device properties due to irradiation.

Since the sample was still "hot" it was then stored for 2 weeks at sub-zero temperature in a fridge for radioactive nuclides to decay to a level where it was safe to characterise the sample. The measurements were performed soon after the device was removed from the fridge. These measurements were used as a starting point and were labelled 0 which implied day 0, and was a standard against which the subsequent time intervals were compared. After these first measurements, the device was kept in the test fixture for, 225 days, the duration of the study. The subsequent measurements were carried oud only when the room temperature was 300 ± 2 K. As a result, the measurements were carried out in no specific days intervals since the temperature would be higher or lower than 300 ± 2 K for some other days.

3. Results and discussion

The results are presented in terms of the current measured in both bias directions and this gives a measure of the carrier density in the material. The irradiation causes damage to the silicon by creating defect levels in the energy gap [11,21–25]. To investigate the behaviour of the conductivity with time after radiation damage, *I–V* measurements were performed at successive periods. The *I–V* profiles generated were, in turn, used to generate several trend plots for various fixed voltages. Two specific plots are presented at 0.2 V for forward bias measurements and at 90 V for reverse bias measurements.

3.1. Forward bias

The data acquired at forward bias appear, at first glance, to be haphazard and confusing. Initially, there is a fall in current but after about 100 days the current increases. This is shown in Fig. 1 where the profile of 42 days is positioned below that of 0 days and the profile of 74 days is below that of 42 days. However, after 74 days the profiles tend to be bundled together and this indicates that there is very little change. After this bundling together of the profiles the current then starts to increase such that after 152 days the profile is positioned above that of 106 days showing that the current has increased.

The data of Fig. 1 were analysed further in order to investigate this "confusing" trend. The forward current measured at 0.2 V was used to generate the trend plot of Fig. 2. This is a plot of the current as a function of the number of days where the current was read off at 0.2 V. It can be noticed from the figure that the measured current is initially high but tends to fall until about 100 days after which it increases. This is a very significant result as it shows that at the start of the measurements the defects are not active and the current is high. This means that most defects are still frozen and do not anneal out.

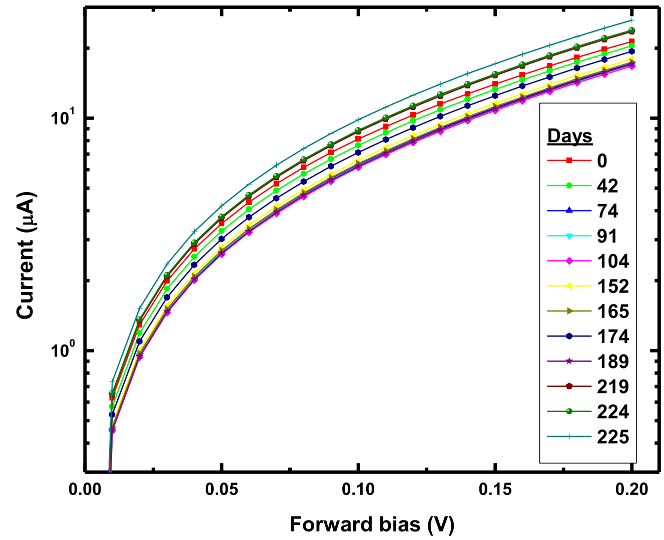

Fig. 1. Current–voltage characteristics of device irradiated to 10^{14} n-cm^{-2} measured at forward bias and at room temperature. The data were taken to study reverse annealing effects.

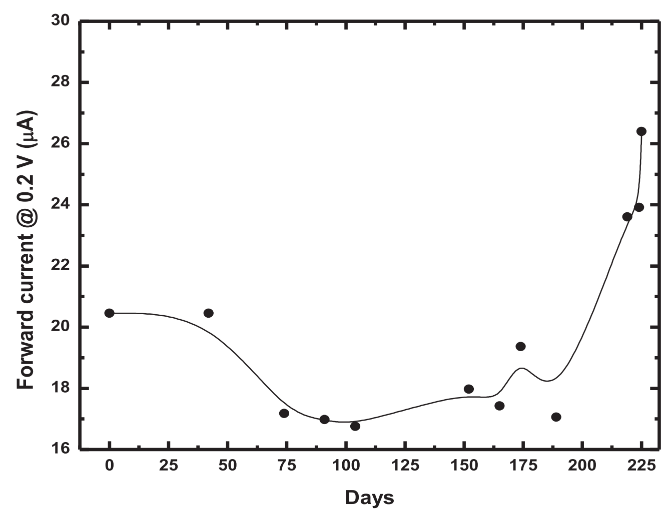

Fig. 2. The trend plot of forward current measured at 0.2 V for device irradiated to 10^{14} n-cm^{-2}. The data are generated from Fig. 1 to investigate reverse annealing effects.

It can be seen from the figure that the current begins to slowly increase after 100 days. This may suggest that the number of defects has decreased or that they act more as generation centres. The first case is more probable since it is known that reverse annealing "repairs" the material to reduce the number of defects [24,26,27]. The data presented here, however, suggests that it is also plausible that some defects do not anneal out and these tend to alter their behaviour or activity and act more as generation centres. The result in either case is that the measured current increases.

It has to be noted that the work presented in Ref. [22] investigated the annealing behaviour of the defects with continued radiation fluence. The work in that case argued that the defects are stable and do not anneal out with fluence. This study is, however, reporting on the behaviour of the defects with time after irradiation by single fluence. The contention here is that some defects do anneal out with time resulting in reduction of device conductivity.

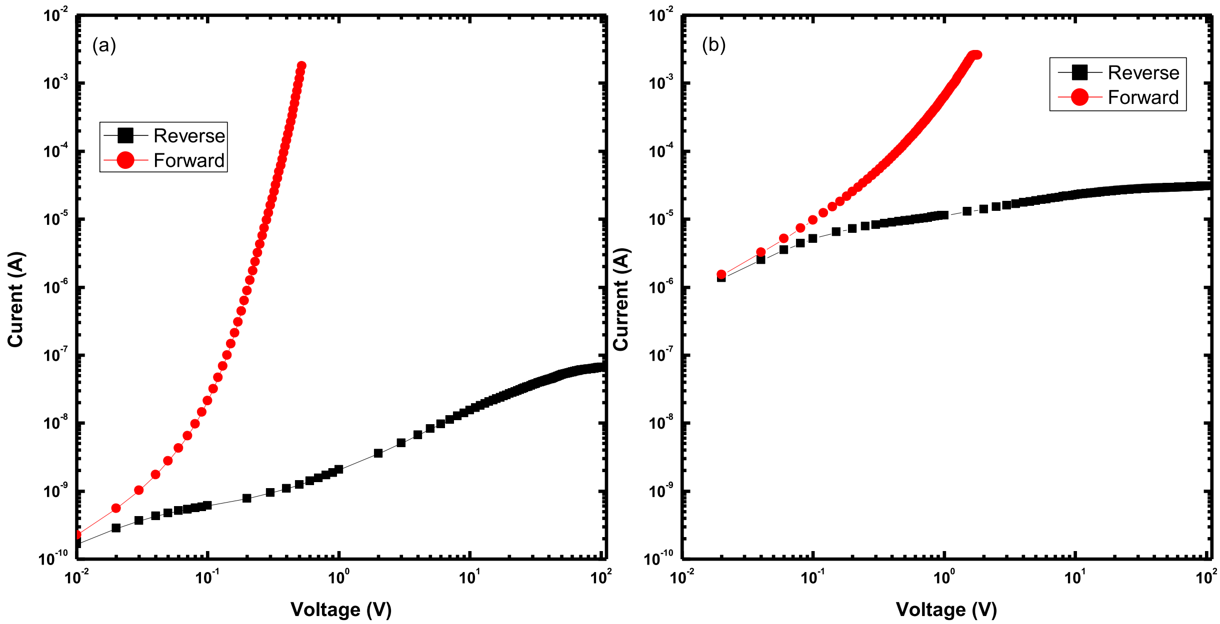

Fig. 3. *I–V* plots for unirradiated (a) and irradiated devices (b) in both bias directions. The data are presented in logarithmic format to better highlight the relaxation behaviour.

Fig. 3 shows *I–V* characteristics of the unirradiated device and the device irradiated to 10^{14} n-cm^{-2}. As expected, the unirradiated device (Fig. 3(a)) shows a typical *I–V* behaviour with a considerable gap between forward and reverse trends [4]. Fig. 3(b), on the other hand, shows that the current of the irradiated device has increased and the gap between the trends has reduced indicating that the current has become ohmic. This ohmic behaviour is pronounced at low voltage region and it indicates that silicon has acquired relaxation-likeness [9–12]. The increase in current has been explained elsewhere in terms of radiation induced defect levels that are responsible for generation of carriers to increase the device conductivity [28].

The relaxation behaviour of the sample is due to high density of generation–recombination centres [10] introduced in the energy gap of the material. These are defect levels that are situated at the centre of silicon energy gap and they interact equally with both bands to maintain the carrier density at intrinsic value [11]. Devices that are fabricated on relaxation material show ohmic behaviour at low voltage region. The data presented in Ref. [12] showed that the ohmic region increases with radiation fluence for 1 MeV neutrons.

Based on the *I–V* plot presented in Fig. 3(b), it cannot be true then that all the defects have annealed out. This has also been observed before [11] where a device irradiated to 3.9×10^{13} n-cm^{-2} had a very high charge collection efficiency (cce). The only logical suggestion then is that some defects do not anneal out with time for single radiation dose and this is in agreement with the argument of Refs. [11,29] based on the data acquired from the devices irradiated to different fluences. These defects then alter their activity and increase diode conductivity an increase in conductivity after the annealing period of 100 days was also observed on the devices that were irradiated to the different fluences up to 50×10^{14} n-cm^{-2} [29]. A particular defect centre is the 701 meV centre, the energy below conduction band minimum at E_c – 0.42 eV, that tends to act more as a generation centre than as a recombination centre [22] to increase the carrier density hence the device conductivity.

3.2. Reverse bias

Reverse annealing data were also acquired at reverse bias and the profiles are shown in Fig. 4. In this case, the measurements were performed up to a reverse bias of 100 V, the maximum reverse voltage to be applied as quoted by manufacturer. The trend shown in the figure is similar to that depicted in Fig. 1. The profiles are initially positioned below the 0 days profile and become bundled together for many days. After this bundling together the profiles then shift upwards to higher currents where after 225 days they are above the 0 days profile.

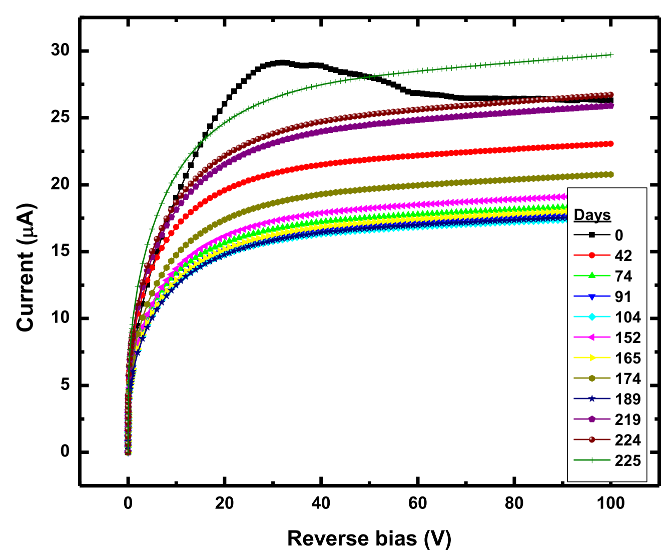

Fig. 4. Current–voltage characteristics of device irradiated to 10^{14} n-cm^{-2} measured at reverse bias and at room temperature. The data are taken to study reverse annealing effects.

Of great interest in this figure is the profile at 0 days, which shows a hump at a bias of about 30 V. This hump is a feature of heavily irradiated silicon that becomes damaged to behave in a relaxation-like manner and is due charge enhancement in the depletion [9,10]. This hump has been observed before [10] by *C–V* data for a device irradiated to 3.4×10^{13} n-cm^{-2} but at lower voltages of about 2 V. It occurs at higher voltages here because the sample has been irradiated to a much higher fluency of 10×10^{13} n-cm^{-2}. The effect has also been observed on diodes made of gold-doped silicon [30] where the hump was positioned at about 2.5 V. It is, however, noticeable that once the applied bias is large enough to draw out the charges contributing to the

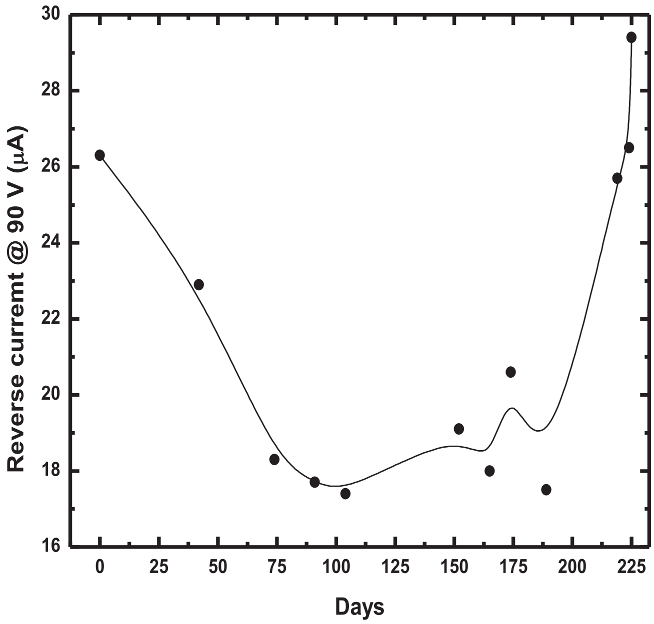

Fig. 5. The trend plot of reverse current measured at 90 V for device irradiated to 10^{14} n-cm^{-2}. The data are generated from Fig. 4 to investigate annealing effects.

enhancement, the measured current falls as carriers are drawn to the opposite electrodes.

The data of Fig. 4 were used to generate the plot shown in Fig. 5. The current measured at 90 V is plotted as a function of the number of days. In the figure, the trend mentioned previously in Fig. 2 is clearly shown where the current falls steadily from a maximum of 26 μA to about 18 μA at around 100 days. After this period the measured current increases steadily. In the figure, the "instability" that is observed around 175 days is overlooked and the trend is smoothed to a gentle curve. This instability is a very important effect and shows that a "repair" in the material is not a regulated process. Since this instability occurs when the current begins to increase, the results may also suggest that the repair occurs as existing defects begin to alter their activity. Thus, the 175 days is a key period in reverse annealing studies. Though they were not thoroughly interpreted, similar results were obtained by Ruzin et al. [18] based on the devices irradiated to 1.46×10^{14} n-cm^{-2}.

Notwithstanding the preceding argument, the general trend of a fall in current up to 100 days followed by a rise from 175 days is observed. This trend depicts the behaviour of the defects do not anneal out and change their activity in the material to become more generation than recombination centres, hence, increase the device conductivity. This change occurs after about 6 months, a period which must be important in reverse annealing studies.

4. Conclusions

It has been shown by *I–V* data that the current measured in irradiated diodes initially decreases with time but after a certain period it begins to increase. The current decreases because in the reverse annealing process the number of defects is being reduced. Any defect centres that do not anneal out in this period alter their activity and increase the measured current. It is suggested that the particular defect is the 701 meV defect, the energy below the conduction band minimum at $E_c - 0.42$ eV, *g–r* centre which acts more as a g-centre than an r-centre to increase the device conductivity. This change occurs at 6 months, a period which should be key to reverse annealing studies of the devices irradiated to 10^{14} n-cm^{-2}. Investigations to this effect are ongoing with samples irradiated to higher fluencies. It is expected that DLTS measurements will reveal that this defect is still present. We are in the process of performing these measurements.

Acknowledgements

We acknowledge the continued discussions with BK Jones on relaxation theory. This work is based on the research supported wholly by the National Research Foundation of South Africa (Grant numbers 105292 and 114800)

References

[1] A. Rose, Phys. Rev. 97 (1955) 1538.
[2] M.A. Lampert, Phys. Rev. 103 (1956) 1648.
[3] R.D. Larrabee, Phys. Rev. 121 (1961) 37.
[4] S.M. Sze, Physics of Semiconductor Devices, 2nd ed., Wiley, New York, 1981.
[5] V.A.J. Van Lint, Nucl. Instr. Meth. A 253 (1987) 453.
[6] F. Lemeilleur, M. Glaser, E.H.M. Heijne, P. Jarron, E. Occelli, IEEE Trans. Nucl. Sci. 39 (1992) 551.
[7] M. Moll, et al., Nucl. Instr. Meth. A 388 (1997) 335.
[8] Z. Li, W. Chen, H.W. Kraner, Nucl. Instr. Meth. A 308 (1991) 585.
[9] B.K. Jones, J. Santana, M. McPherson, Nucl. Instr. Meth. A 395 (1997) 81.
[10] M. McPherson, Nucl. Instr. Meth. A 488 (2002) 100.
[11] M. McPherson, Radiat. Eff. Def. Solid 158 (2004) 45.
[12] S.J. Moloi, M. McPherson, Physica B 404 (2009) 3922.
[13] E. Fretwurst, et al., Nucl. Instr. Meth. A 342 (1994) 119.
[14] A. Ruzin, et al., Nucl. Phys. B (Proc. Suppl.) 78 (1999) 645.
[15] S. Seidel, Nucl. Instr. Meth. A (2001) 1.
[16] V. Khomenkov, et al., Nucl. Instr. Meth. A 568 (2006) 61.
[17] A. Wiik-Fuchs et al., Nucl. Instr. Meth. A (2018), in press.
[18] A. Ruzin, et al., Nucl. Instr. Meth. A 426 (1999) 94.
[19] D. Pitzl, et al., Nucl. Instr. Meth. A 311 (1992) 98.
[20] Hamamatsu Photonics K.K., Hamamatsu City, Japan.
[21] Chengji Li, Zheng Li, Nucl. Instr. Meth. A 342 (1994) 137.
[22] M. McPherson, Curr. Appl. Phys. 2 (2002) 359.
[23] D. Menichelli, et al., Nucl. Instr. Meth. A 530 (2004) 139.
[24] Z. Li, et al., Nucl. Instr. Meth. A 699 (2013) 1.
[25] E.M. Donegani, et al., Nucl. Instr. Meth. A 898 (2018) 15.
[26] P.P. Allport, et al., Nucl. Instr. Meth. A 420 (1999) 473.
[27] E. Gaubas, et al., Mater. Sci. Semicond. Process. 75 (2018) 157.
[28] A. Hamache, et al., Radiat. Phys. Chem. 123 (2016) 103.
[29] I. Mandic, et al., Nucl. Instr. Meth. A 629 (2011) 101.
[30] M. Msimanga, M. McPherson, Mater. Sci. Eng. B 127 (2006) 47.