RADIATION EFFECTS IN SILICON DETECTORS PROCESSED ON CARBON AND OXYGEN RICH SUBSTRATES

A. Ruzin[*], G. Casse[*], M. Glaser[*], F. Lemeilleur[*], J. Matheson[*], S. Watts[**], A. Zanet[*]

[*]CERN, EP Division, CH-1211 Geneva, Switzerland
[**]Brunel university, Uxbridge, UB83PH, UK

CERN RD-48 (ROSE) Collaboration

ABSTRACT

Radiation hardness results of silicon detectors fabricated on bulk float zone (FZ) material enriched either by carbon or by oxygen are reported. The detectors were irradiated by nuclear reactor neutrons, by 24 GeV/c protons and by 192 MeV pions. It has been shown that the leakage current increases with fluence equally in all silicon detectors under study, regardless of the oxygen or carbon concentrations. The variations in the space charge density were found to be very different in the oxygen and carbon enriched materials in the case of irradiation by charged particles, yet rather similar in case of neutrons. When irradiated to high fluences by protons and pions, the detectors fabricated on oxygen enriched float zone (FZ) silicon had significantly lower full depletion voltages compared to the detectors fabricated on standard FZ material. The opposite effect has been observed with carbon enriched FZ silicon detectors. The practical implication of that result is that silicon detectors can be designed to operate longer in harsh radiation environments where protons and pions are present.

1. INTRODUCTION

1.1 Background

This study was motivated to a large extent by the needs of the future high-energy physics experiments. The experiments associated with the Large Hadron Collider (LHC) at CERN, for example, will use large numbers of silicon detectors, covering area of many square meters, in their tracking systems. Some experiments are designed to operate during periods of ten years and more. During the years of operation the detectors will be exposed to high fluxes of various particles, which will induce significant lattice damage in the crystalline semiconductors. Some of the radiation induced defects are electrically active and alter the operation of the detectors. Two of the most challenging alterations due to the radiation damage are the increase of the leakage current and the variation of the full depletion voltage. The detectors are designed to operate fully depleted and even over-depleted, since the generated charge signal is mainly collected from the region where significant electric field is present. The charge collection issue will become more critical as traps will be introduces by the radiation. The increase of leakage current leads to increase in noise and power consumption. The study is carried out in the framework of CERN RD-48 (ROSE) collaboration, which was established to investigate the various aspects of radiation hardness of silicon detectors and to look for ways to improve it. It should be noted that the term 'radiation hardness' describes the general criteria of detector's useability. Detectors that can be operated with adequate performances up to a higher fluence, have a better radiation hardness.

1.2 Damage generation

Photons with energy range of 1-7 MeV are capable to cause atom displacements from the lattice mostly via collisions of secondary electrons. The secondary electrons can be generated by three mechanisms: photoelectric effect, Compton scattering, and electron-positron pair production. Electrons with kinetic energies of few MeV can only create Primary Knock-on Atoms (PKA) with low kinetic energies, due to the large mass difference [1]. Such electrons can produce only a few displacements each. The generated interstitials and vacancies diffuse in the lattice until create stable complexes, such as multi-vacancies, etc. In that case the stable defects would be distributed in the lattice, rather than concentrated near the interaction sites.

The effect of hadron interaction is quite different. The energy transfer to the PKA could be up to 130 keV in the case of 1 MeV neutron collision with a silicon atom. The displacement energy threshold of a single atom is estimated to be 12.9-30 eV [1-4], therefore, the total number of displaced atoms in vicinity of PKA can reach several thousands. The generated interstitial-vacancy concentration is therefore high, and about 95% of the damage is believed to recombine immediately without a trace [5]. Due to the high initial concentrations of vacancies and interstitials following the interaction, some of them form stable complexes, which are immobile, forming *clusters* of localized defects. The vacancies and interstitials that do not recombine or form stable complexes diffuse in the lattices. The resulting damage is therefore different qualitatively from the damage of photons, in it's partially clustered nature.

1.3 Non Ionizing Energy Loss (NIEL)

The fraction of the energy transferred by the incident particle to the lattice not via ionization is called *Non Ionizing Energy Loss (NIEL).* The energy is proportional to the amount of displacements produced in the chain of interactions. In radiation hardness tests, often it is not possible to create radiation environment similar to that of the real scenario. In addition, irradiation facilities are limited in the particle types and the energies. Therefore, the NIEL factor is often used in order to calculate equivalent fluences of various particles, namely, fluences that would cause similar damage. The most common standard for comparison is that of 1 MeV neutrons. There are calculated and measured data of NIEL factor in the literature for electrons, protons, pions, neutrons and ions in a wide energy range [6-8].

2. EXPERIMENTAL

2.1 Material

All reported devices are PIN diodes, with a 5mm×5mm contact surrounded by a guard ring. The 'intrinsic' region of the diodes is initially n-type Float Zone (FZ) silicon with resistivity range 1.3-6 kΩ·cm. The thickness of the tested devices is 280-300 μm. Oxygen enrichment was done by two methods: diffusion of oxygen from SiO_2 layer at 1150°C lasting 24-72 hours [9], and introduction of oxygen gas jet during the FZ growth process [10,11]. After oxygen diffusion of 48 and 72 hours, a rather uniform oxygen concentration of $\sim 2\times10^{17}$ cm^{-3} has been measured by SIMS method [12]. After 24 hours of oxygen diffusion, the oxygen concentration is somewhat less uniform but remains above 2×10^{17} cm^{-3} throughout the wafer. Carbon concentration in all oxygen-diffused wafers is below the background level of the measurements, 1×10^{16} cm^{-3}. The concentration of oxygen in the material enriched by the gas flow is similar to that achieved by diffusion of 48 or 72 hours. Carbon concentration in the oxygen-jet enriched samples is approximately 9×10^{15} cm^{-3}. Relatively high concentration of carbon, 1.8×10^{16} cm^{-3}, and low concentration of oxygen (bellow the background level of $\sim 5\times10^{16}$ cm^{-3}), has been obtained in FZ silicon by diffusion from Czochralski (Cz) poly-crystalline wafers. First, a small piece of graphite was melted in silicon poly-crystalline. Then, a wafer of this carbon-enriched poly-silicon was placed between a standard FZ poly-silicon ingot and the seed. Finally, a standard FZ growth process was performed [13,14]. Wafers diffused with oxygen and standard wafers, used for comparison, originate from the same ingot grown at Polovodice [14]. All samples reported in this work were processed by ITE [9].

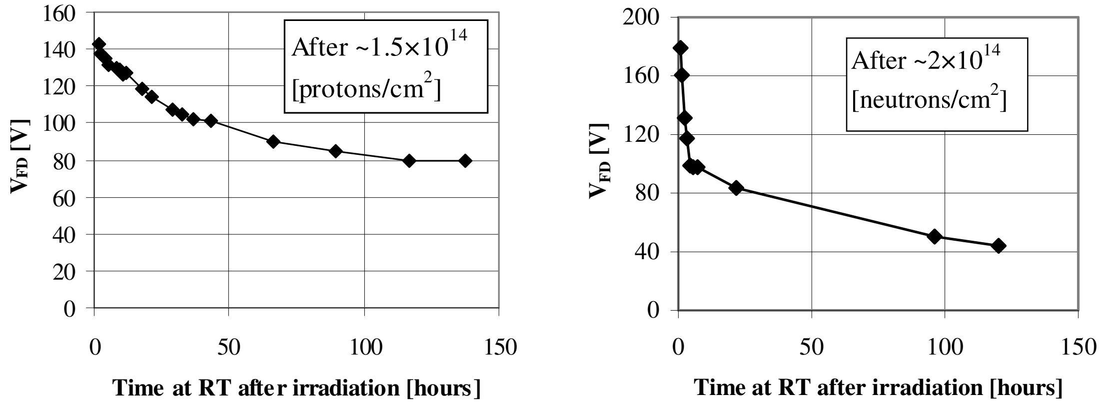
2.2 Irradiation facilities

The detectors were irradiated by 24 GeV/c protons, nuclear reactor neutrons and 192 MeV pions (π^+). The irradiation with protons was performed at CERN Proton Synchrotron (PS). The theoretical value of NIEL factor for the specific energy is not found in the literature, however the hardness factor of 24 GeV proton relative to 1 MeV neutrons can be roughly extrapolated to a value 1-1.2 from Ref. [6] or to a value 0.5-0.7 from Refs. [7,8]. The neutron irradiation was performed at Triga type nuclear reactor [15]. The neutron energy spectrum in the core of the reactor is ranging from thermal to around 10 MeV, with a total relative hardness factor of ~0.88 [16]. Pion irradiation was performed at PSI, Villigen [17]. Pions with kinetic energy of 192 MeV have a theoretical hardness factor of ~0.9 relative to 1 MeV neutrons [6].

2.3 Short term annealing procedure and measurements

Following the introduction of damage by irradiation defect reorganization takes place, according to the described in section 1.2. The phenomena of annealing are often referred to as *beneficial annealing* and *reverse annealing*, as will be further discussed in section 3.

Recently it has been noticed that the short-term component of the annealing has not been sufficiently appreciated. In the case of proton and pion irradiations, intermediate and high fluences are accumulated within hours of irradiation. During the irradiation process, the holder set up and the environment become radioactive and require ‘cooling’ period before the detectors can be extracted and measured. Most of the irradiation experiments are performed around room temperature. Therefore, a significant so called self-annealing takes place before the detectors are measured. In the case of irradiation with nuclear reactor, the time required can be very short, for instance fluence of 6×10^{14} cm^{-2} can be accumulated in as little as 4 minutes. The ‘cooling’ period is also shorter due to the geometry of the operation that does not require physical access to the irradiation zone. Therefore, the effect of the self-annealing is significantly reduced. Typical short-term evolutions of the full depletion voltages with time after irradiation for protons and neutrons are shown in Fig. 1.

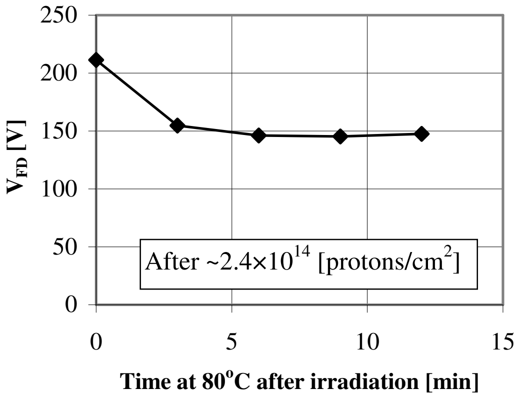


(a) (b)

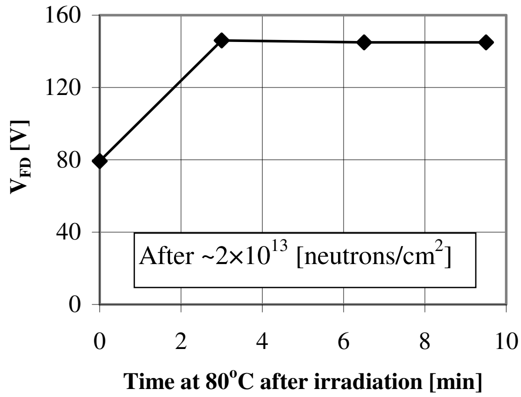
<u>Figure 1</u>: Short-term annealing after hadron irradiation. Evolution of full depletion voltage versus time at room temperature: (a) with protons; (b) with neutrons.

In the case of annealing after neutron irradiation, which is described in Fig. 1(b), the full depletion voltage falls from about 180 V to less than 100 V within ~ 4 hours. After that the annealing continues with a moderate time constant. The sharp drop in full depletion is not observed in the case of proton irradiated detector, probably due to the longer irradiation and ‘cooling’ periods, as described above. It should be noted that after about 10 days at room temperature, the value of full depletion voltage stabilizes for approximately 20 days, before it starts increasing. The full description of annealing behaviour is in section 3.

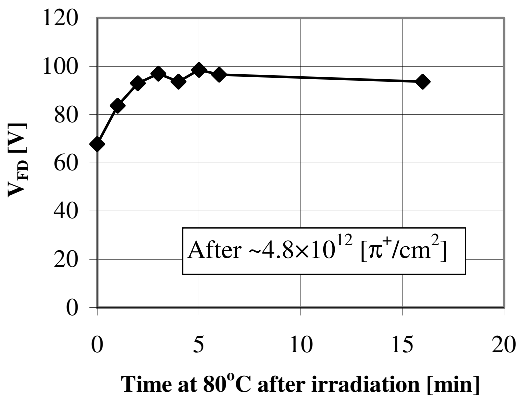
Two major issues have to be addressed following this observation: when to perform the measurements and how to compare irradiations performed at various facilities and/or with different fluxes (namely, different irradiation times). We have proposed to perform the measurements at the end of the beneficial annealing, when the full depletion reaches the plateau. Consequently, the measurements are more stable and the self-annealing, which occurs during the few hours of irradiation is negligible compared to 10 days. In addition, such measurements closer resemble the ‘real life scenario’ of detectors in LHC experiments, since the fluence will be accumulated during years and not hours. Therefore, continuous annealing will take place even bellow 0°C. However, waiting 10 days after each irradiation step is often impossible due to practical considerations. Therefore, we propose to perform thermally enhanced annealing process. It has been noticed that heating irradiated detectors above 80°C, causes significant generation and activation of bistable defects [18]. The variation of full depletion voltage versus annealing time at 80°C for proton, neutron and pion irradiated detectors are shown in Fig.2. It should be noted that for proton irradiated detector the full depletion voltage is decreasing, while for the neutron and pion irradiated detectors the full depletion voltage increases. The reason is that the former detector is type inverted whereas the latter are not. In general, it seems that the annealing time at 80°C that is required to reach the plateau in full depletion voltage is rather similar. Hence, following each irradiation step we heat the detectors for 4 minutes at 80°C before measurement.



(a)



(b)



(c)

<u>Figure 2</u>: Thermally enhanced short-term annealing after hadron irradiation. Evolution of full depletion voltage versus heating time: (a) at 80°C with protons; (b) at 80°C with neutrons; (c) at 80°C with pions.

3. RESULTS AND DISCUSSION

Throughout the study special emphasis was made on the comparative approach. The flux calibration might change sometimes by as much as 20 % from one irradiation period to another, in particular in the case of nuclear reactor, where the neutron spectrum is wide and depends on the core configuration. However, within each irradiation experiment we have irradiated the detectors simultaneously and measured them under similar conditions. Therefore, the comparison of behaviour of the various detectors irradiated at the same irradiation run is accurate within about 5%. The comparison between the various irradiation runs is also possible, but with a larger error.

3.1 Space charge density

It is believed that the radiation-induced defects form deep levels, in particular acceptors near mid gap. Such levels in the forbidden gap trap electrons from the valence band as well as from the conduction band, reducing the free carrier concentration. The Fermi level is therefore lowered towards the intrinsic level. However, the material can not become a strong p-type, since for that to happen, the Fermi level has to go far bellow mid gap, in which case the deep acceptors would release the electrons. The material therefore remains nearly intrinsic with the Fermi level pinned to the region of the deep levels.

Under reverse bias conditions the situation is quite different. In the depleted region the concentration of free carriers is very low, therefore the deep acceptors can capture electrons only from the valence band and emit electrons only to conductance band. Under steady state conditions, the successive capture and release of electrons, maintain a fraction of the acceptors occupied by electrons. The fraction is proportional to the capture and emission constants, following the standard Shockley-Read-Hall (SRH) statistics,

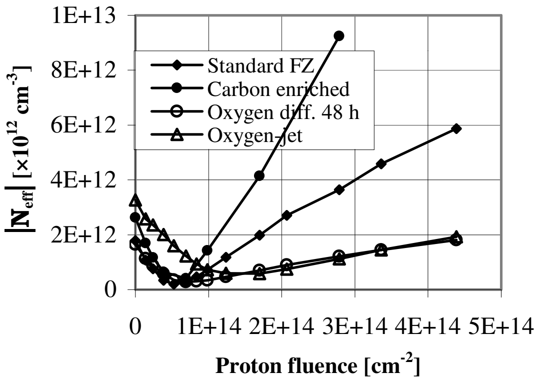
$$N_t^- = \frac{N_t}{1 + e_n / e_p} \qquad (1)$$

where N_t is the total concentration of deep acceptors, N_t^- is the concentration of the acceptors occupied by electrons, e_n is the electron capture constant, and e_p is the electron emission constant. In the experiment we deduce the average space charge density, N_{eff}, from measurement of full depletion voltage, V_{FD}. The relation is given by Eq. 2, where $\varepsilon_0 \cdot \varepsilon_{Si}$ is the permittivity of silicon, q is the electron charge, d is the effective thickness of the detector and V_{bi} is the built-in voltage of the p^+-n^- junction.

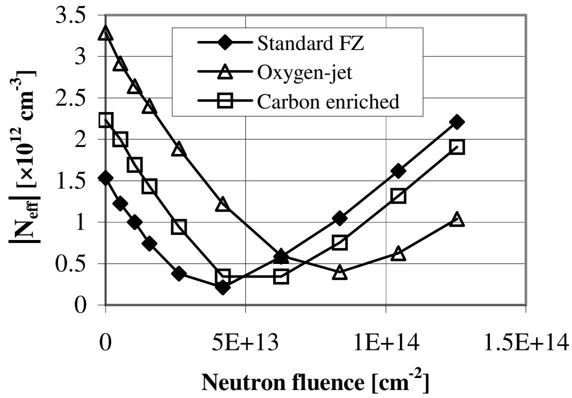
$$\left| N_{eff} \right| = \frac{2 \cdot \varepsilon_0 \cdot \varepsilon_{Si} \cdot (V_{FD} + V_{bi})}{q \cdot d^2} \qquad (2)$$

The value of V_{FD} is extracted from the capacitance-voltage (C-V) profile. Therefore, the experimentally obtained N_{eff} is the sum of the charge of the shallow donors, namely phosphorus, and the charged levels introduced by defects in the forbidden gap.

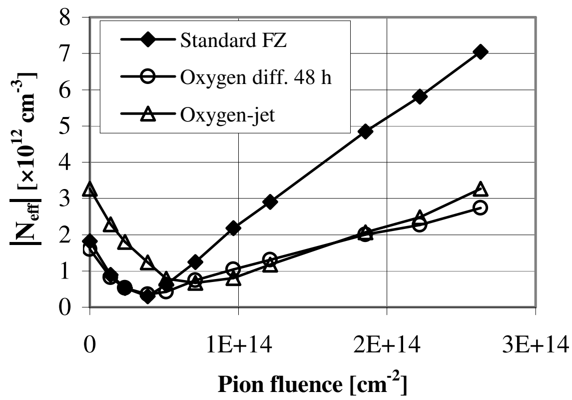
The general trend of the N_{eff} evolution with increasing fluence is similar for all detectors and irradiating particles as shown in Fig.3. At low fluences the N_{eff} is reducing due to formation of deep acceptors, that contribute negative space charge, and possibly due to reduction in effective donor concentration, due to formation of E-centres (VP).



(a)



(b)



(c)

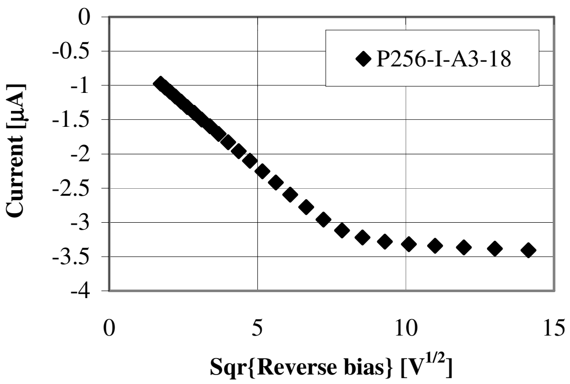
Figure 3: Dependence of the effective space charge density of a fully depleted detector, N_{eff}, on the accumulated particle fluence.: (a) Irradiated with 24 GeV/c protons; (b) Irradiated with reactor neutrons; (c) Irradiated with 192 MeV pions.

At certain so-called *inversion fluence*, the total space charge should approach zero, further introduction of defects inverts the sign of the space charge. It should be noted that the polarity of reverse biasing in PIN structure does not change after inversion. In some samples the full depletion voltage approaches zero closer than in others. The reason for that behaviour is not fully understood, but the effect could be explained by material non-uniformity.

In the case of neutron induced damage, shown in Fig. 3(b), the inversion fluence is directly proportional to the initial doping concentration. The N_{eff} gradients of the standard, the oxygen-jet and the carbon-enriched detectors are similar, before as well as after inversion fluence. After proton and pion irradiation, Figs. 3(a) and 3(c), detectors processed from the same wafers as detectors irradiated by neutrons, exhibit different characteristics. The gradient of N_{eff} in carbon enriched detector after inversion is a factor ~3 higher than that of the standard silicon. On the contrary, the gradients for oxygen-jet and for oxygen-diffusion enriched materials are approximately 3 times lower than in standard. Measurements of standard and oxygen enriched detectors irradiated with pions are in agreement with the results of proton irradiation. Namely, it has been found that the introduction rate of negative space charge in oxygen enriched detectors is significantly lower than in standard silicon detector in cases of protons and pions, yet the rate seems to be similar in the case of neutrons. Therefore, fluence normalization to the equivalent of 1 MeV neutrons, as described in paragraph 1.3, is not valid for oxygen and carbon enriched silicon. Regardless of the exact NIEL factors ratio, simple multiplication of fluence scale can not convert similar N_{eff} gradients of Fig. 3(b) into different gradients of Figs. 3(a) and 3(c).

3.2 Leakage current

Typical, current-voltage characteristic of a diode irradiated with 1.4×10^{13} protons/cm^2 with iso-potential connected guard ring is shown in Fig. 4.



<u>Figure 4</u>: Current-voltage characteristic under reverse bias of irradiated detector.

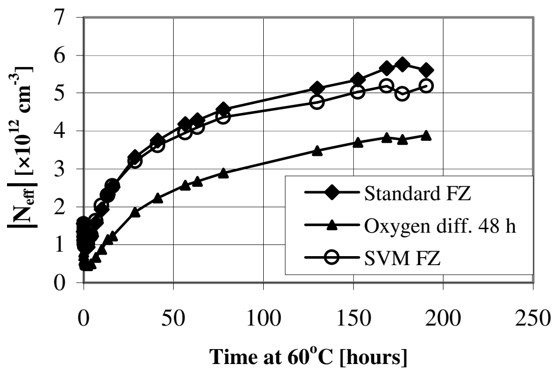
The nearly linear dependence of the leakage current on the square root of the voltage before full depletion, indicates dominant generation current mechanism. Therefore, it is possible to indicate the volume current, namely, the current generated by a unit of depleted volume, as a figure of merit independent of the detector dimensions. The introduction rate of generation centres by irradiating particles is $\alpha = \Delta I_{vol}/\Delta\phi$ with units [A/cm].

Similar value of α parameter was observed for all detector types in each irradiation run. The absolute value of α is strongly dependent on the fluence measurement and calibration, however, the comparative approach of the experiment emphasises the validity of the result.

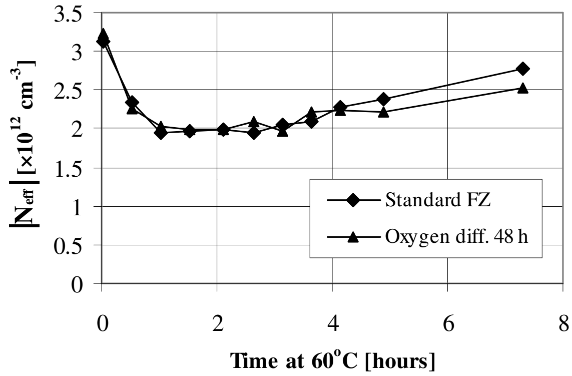
The measured α value for reactor neutrons is ~4×10^{-17} [A/cm], for 24 GeV/c protons ~2.5×10^{-17} [A/cm], and for 192 MeV pions ~5.2×10^{-17} [A/cm].

3.3 Annealing behaviour

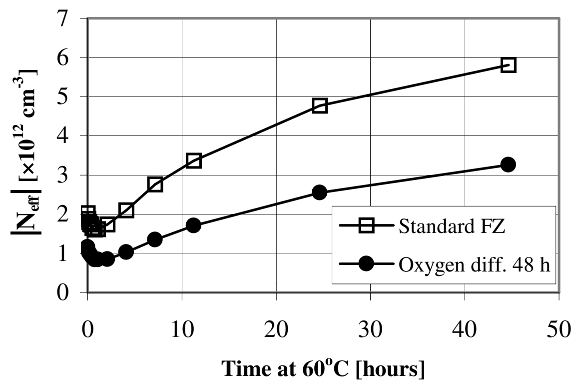
It has been noted that when detectors are stored at room temperature after irradiation their electrical characteristics continue to evolve. It is of great interest from both scientific and application point of view.



(a)



(b)



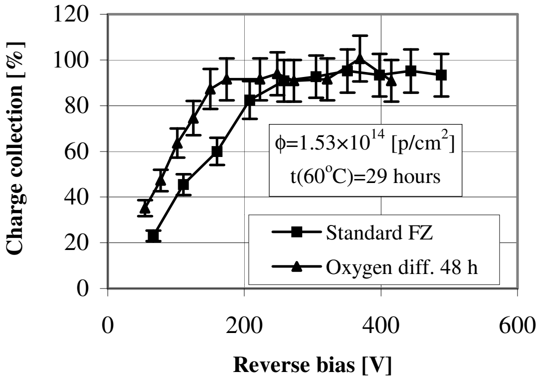
(c)

Figure 5: Dependence of N_{eff} on the annealing time at 60°C after irradiation: (a) Irradiated with 1.52×10^{14} [p/cm^2], 24 GeV/c protons; (b) Irradiated with 1.6×10^{14} [n/cm^2], reactor neutrons; (c) Irradiated with 1×10^{14} [π^+/cm^2], 192 MeV pions.

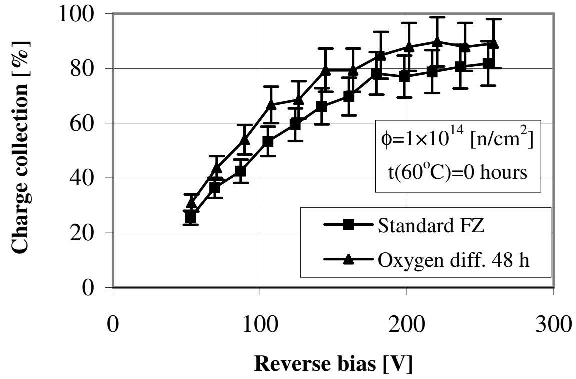
At room temperature the evolution continues for years, therefore for practical reasons it is a common practice to stimulate the aging effect by increasing the temperature [19,20]. The aging effect for the various irradiating particles is presented in Fig. 5. The standard and oxygen enriched detectors in each irradiation experiment were chosen to have similar N_{eff}

prior to the irradiation. In the cases of proton and pion irradiations, described in Fig. 5 (a) and (c), respectively, large difference was observed between standard and oxygen enriched detectors. Immediately after irradiation the N_{eff} of oxygen enriched detectors was almost a factor two lower than that of standard detectors. After heating the effective space charge in the oxygen enriched detectors remains significantly lower compared to the standard ones. In the case of neutron irradiation described in Fig. 5(b), the effective space charge after irradiation is similar in the oxygen enriched and in the standard devices. The heating was done at 60°C for approximately 7.5 hours then the temperature was increased to 80°C. No significant difference was observed in the aging at either temperature. A slightly lower N_{eff} in the oxygen enriched samples was observed after long heating, but the result is on the limit of error bar and the experiment will be repeated.

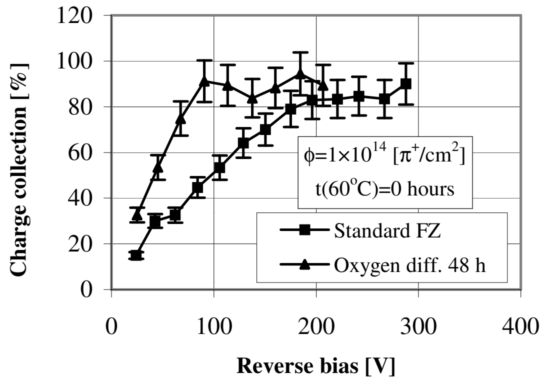
3.3 Charge collection



(a)



(b)



(c)

Figure 6: Charge collection for fast electrons (MIPs) after irradiation: (a) Irradiated with 1.53×10^{14} cm^{-2} protons and measured after 29 hours at 60°C; (b) Irradiated with 1×10^{14} cm^{-2} reactor neutrons and measured after several days at -20°C; (c) Irradiated with 1×10^{14} cm^{-2} pions and measured after several days at -20°C.

For the high energy physics application, probably the most important figures of merit are the charge collection and the signal to noise ratio. The two are related, because higher charge collection increases the signal amplitude. Charge collection was measured in irradiated detectors using minimum ionizing particles (MIPs), specifically electrons from ^{106}Ru radioactive isotope. The beneficial effect of oxygen enrichment is clearly seen in the case of proton and pion irradiation, Figs. 6(a) and 6(c), respectively. Detectors irradiated by protons were annealed for 29 hours at 60°C after irradiation, before the charge collection measurements. Detectors irradiated with neutrons and pions were irradiated and stored at -20°C for several days before measurements. The charge collection in neutron irradiated detectors, Fig. 6(b), seems to be also better in oxygen enriched devices, however the difference is not significant and it is not observed in detectors irradiated to fluences smaller than 1×10^{14} cm^{-2}.

REFERENCES

[1]. Julius H. Cahn, "Irradiation Damage in Germanium and Silicon due to Electrons and Gamma Rays", J. Appl. Phys., Vol. 30, No 8, pp. 1310-1316 (1959).

[2]. J. W. Corbett and G. D. Watkins, "Production of Divacancies and Vacancies by Electron Irradiation of Silicon", Phys. Rev., 138A, pp. 555-560 (1965).

[3]. R. Bauerlein, "Displacement Thresholds in Semiconductors", Radiation Damage in Solids, Edited by D. S. Billington, Academic Press, New York (1962).

[4]. Geoffrey P. Summers, Edward A. Bruke, Philip Shapiro, Scott R. Messenger and Robert J. Walters, "Damage correlations in semiconductors exposed to gamma, electron and proton radiations", IEEE Trans. Nucl. Sci., Vol. 40, No. 6, pp. 1372-1379 (1993).

[5]. George C. Messenger, "A Summary Review of Displacement Damage from High Energy Radiation in Silicon Semiconductors and Semiconductor Devices", IEEE Trans. Nucl. Sci., Vol. 39, No. 3, pp. 468-473 (1992).

[6]. A. Van Ginneken, "Non Ionizing Energy Deposition in Silicon for Radiation Damage Studies", Fermi National Accelerator Laboratory, internal report FN-522 (1989).

[7]. Edward A. Bruke, "Energy dependence of proton-induced displacement damage in silicon", IEEE Trans. Nucl. Sci., NS-33, No. 6, pp. 1276-1281 (1986).

[8]. G. P. Summers, E. A. Bruke, C. J. Dale, E. A. Wolicki, P. W. Marshal and M. A. Gehlhausen, "Correlation of particle-induced displacement damage in silicon", IEEE Trans. Nucl. Sci., NS-34, No. 6, pp. 1134-1139 (1987).

[9]. ITE – Institute of Electron Technology, Al. Lotnikow 32/46, 02-668 Warszawa, Poland.

[10]. E. Nossarzewska-Orlowska, Z. Luczynski, R. Kozlowski, Brzozowski, P. Zabierowski, B. Majerowski, "Characterisation of ITME silicon for detectors", the 3rd ROSE Workshop, DESY-Proceedings-1998-02, February 1998, Hamburg, Germany.

[11]. ITME – Institute of Electronic Materials Technology, ul. Wolczynska 133, 01-919, Warszawa, Poland.

[12]. EVANS EUROPA, Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom.

[13]. Private communication, Prof. Bruno Sopko, department of physics, faculty of mechanical engineering, CTU Prague, Czech Republic.

[14]. POLOVODICE, Vovodvorska 994, 142 21 Prague 4, Czech Republic.

[15]. TRIGA reactor at Jozef Stefan Institute, Ljubljana, Slovenia.

[16]. V. Cindro, G. Kramberger, M. Mikuz, D. Zontar "Bias-dependent annealing of radiation damage in neutron-irradiated silicon p+-n-n+ diodes", Nucl. Instr. And Meth. A 419 (1998) 132-136.

[17]. Paul Scherrer Institute (PSI), Villigen CH-5232, Switzerland.

[18]. M. Moll, H. Feick, E. Fretwurst, G. Lindström and T. Schultz, "Observation of a bistable defect generated and activated by heat treatment in irradiated high resistivity silicon detectors", Nucl. Phys. B (Proc. Suppl.) vol. 44, pp. 468-474 (1995).

[19]. E. Fretwurst, H. Feick, M. Glaser, C. Gössling, E. H. M. Heijne, A. Hess, F. Lemeilleur, G. Lindström, K. H. Mahlmann, A. Rolf, T. Schultz, C. Soave, "Reverse annealing of the effective impurity concentration and long term operation scenario for silicon detectors in future collider experiments", Nucl. Instr. And Meth. A 342 (1994) 119-125.

[20]. Z. Li, W. Chen, L. Dou, V. Eremin, H. W. Kraner, C. J. Li, G. Lindström and E. Spiriti, "Study of the long term stability of the effective concentration of ionized space charges (Neff) of neutron irradiated silicon detectors fabricated by various thermal oxidation processes", IEEE Trans. Nucl. Sci., Vol. 42, No. 4, pp. 219-223 (1995).

Keywords

Radiation hardness, oxygen-enriched, carbon-enriched, silicon, PIN detectors, pions, protons, neutrons