EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–EP/98–62
11 Juin 1998

STUDIES OF THE RADIATION HARDNESS OF OXYGEN-ENRICHED SILICON DETECTORS

A. Ruzin, G. Casse[1)], M. Glaser, F. Lemeilleur
CERN, Geneva, Switzerland

Abstract

Detectors of high-energy particles sustain substantial structural defects induced by the particles during the operation period. Some of the defects have been found to be electrically active, degrading the detector's performance. Understanding the mechanisms of the electrical activities and learning to suppress their influence are essential if long 'lifetime' detectors are required. This work reports about radiation hardness of silicon P-I-N devices fabricated from oxygen-enriched, high-resistivity material. The high and nearly uniform concentration of oxygen in float-zone silicon has been achieved by diffusion of oxygen from SiO_2 layers.

Presented at the 2nd International Conference on Radiation Effects on Semiconductor Materials, Detectors and Devices, Florence, 4–6 March 1998

[1)] Associazione per lo Sviluppo Scientifico e Tecnologico del Piemonte (ASP)

1 INTRODUCTION

Future experiments in high-energy physics at the CERN Large Hadron Collider (LHC) will employ silicon detectors at various positions around the beam crossing points. The detectors are exposed to high fluxes of particles and during the years of operation sustain significant radiation damage. Some of the radiation-induced defects are electrically active and alter the operation of the detectors. The RD48 (ROSE) Collaboration was founded to study and to improve the radiation hardness of silicon detectors. Two of the most challenging operation alterations owing to the radiation damage are the increase of the reverse DC current and the variation of the full depletion voltage. It has been suggested [1, 2] that the electrically active defect responsible for the formation of positive space charge under bias is the divacancy–oxygen complex, V_2–O. Therefore, by increasing the concentration of oxygen and enhancing the formation of V–O complexes, it has been predicted that the concentration of vacancies will be reduced, leading to the suppression of the V_2–O formation.

The concentration of oxygen in standard float-zone (FZ), high-resistivity silicon is substantially lower than that in Czochralski material and does not exceed ~ 5×10^{15} at/cm^3. Several attempts to achieve high concentration of oxygen in FZ material during the growth process had only partial success. A previous study by Z. Li et al. was performed on silicon samples with 15-μm layers of diffused oxygen [3].

Here we report the first successful achievement of nearly homogeneous oxygen concentration above 2×10^{17} at/cm^3 in 300-μm thick wafers by diffusion of oxygen from SiO_2 layers at high temperature. P-I-N devices were fabricated from this oxygen-enriched material and the radiation hardness tested.

2 EXPERIMENTAL

Standard 3-in. n-type, high-resistivity, FZ silicon wafers were double-side polished to 300-μm thickness and layers of ~ 300 nm of local oxide were grown on both sides by the dry oxidation technique. The wafers then were heated to 1150°C in a nitrogen atmosphere to allow desorption of oxygen from the SiO_2 at the interface and it's diffusion into the bulk. Wafers were divided in three groups, with different diffusion periods of 24, 48 and 72 hours. The concentration of oxygen in the FZ silicon has been measured after the diffusion by Secondary Ion Mass Spectroscopy (SIMS), as well as by infrared spectroscopy. Resistivity profiles were measured, by the spreading resistivity method at ITME [4], in order to study the possible influence of the oxygen atoms as thermal donors.

Shallow-junction P-I-N diodes of 5×5 mm^2 with guard rings were fabricated by ITE [5] from the three groups of oxygen-diffused material as well as from a similar standard silicon. Devices of all four groups were characterized by current–voltage, capacitance–voltage, charge collection efficiency for Minimum Ionizing Particles (MIPs) from a ^{106}Ru electron source, as well as minority lifetime measurements by the reverse recovery method [6].

The detectors were irradiated by fast neutrons at a research reactor in Ljubljana [7] to fluences ranging from 5×10^{12} to 2.5×10^{14} neutron/cm^2 (not normalized to 1 MeV neutrons). The relative damage coefficient to 1 MeV neutron equivalent has been calculated to be ~ 0.88 [8]. A set of detectors fabricated from 24 hours, 48 hours and 72 hours oxygen-diffused materials, as well as from reference FZ silicon was irradiated in 10 successive steps and analysed within 40 minutes after each irradiation step. The irradiation and measurements were performed at 18°C.

3 RESULTS AND DISCUSSIONS

3.1 Oxygen diffusion

Figures 1 (a) and (b) show the oxygen and carbon concentration profiles, respectively, measured with the SIMS method by EVANS [9]. It is evident that after 72 hours of diffusion the concentration profile of oxygen in the bulk is nearly uniform up to a thickness of 150 μm. Since oxygen from SiO_2 was diffused from both sides into the 300−μm thick wafer, the overall concentration in the bulk is practically uniform. This is the first time that such high and uniform concentration of oxygen (~ 2×10^{17} at/cm^3) has been achieved in high-resistivity FZ silicon. The resistivity of the material after the diffusion has been found to decrease by a factor of ~ 1.7, maintaining the resistivity above 1.8 k• cm.

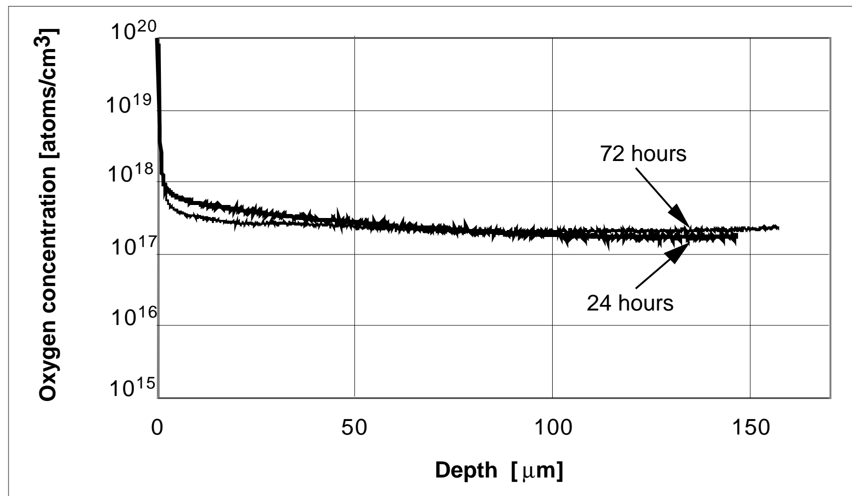


Figure 1(a): Depth profiles of oxygen, measured by secondary ion mass spectroscopy.

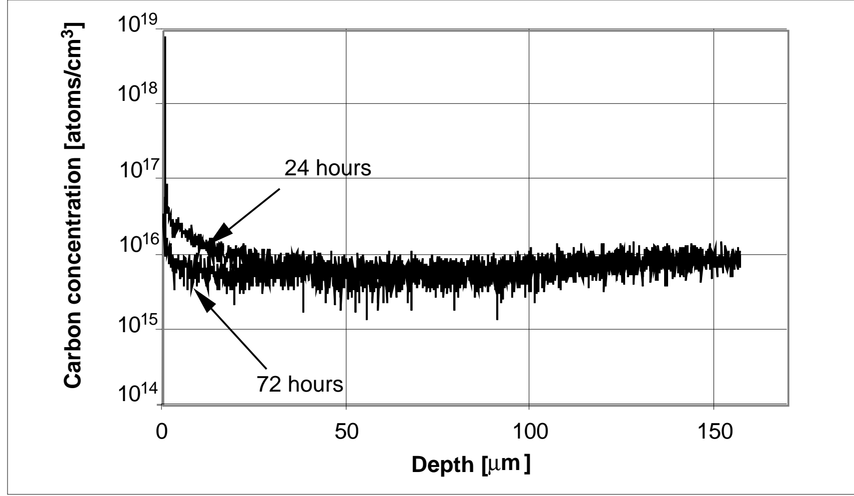


Figure 1(b): Depth profiles of carbon, measured by secondary ion mass spectroscopy.

3.2 Full-depletion voltage

The full-depletion voltage has been evaluated from capacitance–voltage measurements, by finding the intersection point of the two different slopes on a logarithmic scale. The full depletion voltage, V_{FD}, is proportional to the space charge density in the depletion region, N_{eff} :

$$V_{\mathrm{FD}} = \frac{q \cdot d^2 \cdot N_{\mathrm{eff}}}{2 \cdot \varepsilon_0 \cdot \varepsilon_{\mathrm{Si}}} \tag{1}$$

were q is the electron charge, d is the thickness of the detector, ε_0 is the permittivity of vacuum and $\varepsilon_{\mathrm{Si}}$ is the relative permittivity of silicon.

The dependence of full-depletion bias voltage on the accumulated neutron fluence is presented in Fig. 2. At low fluences the full-depletion voltage decreases exponentially, suggesting deactivation of existing donors. The inversion of space-charge sign due to linear introduction of acceptor-like defects and deactivation of the existing donors takes place at a fluence of ~ 2×10^{13} cm^{-2} for all four types of detector. Beyond that fluence, a nearly linear increase of the full-depletion voltage, indicating a corresponding increase of the effective space-charge density, is observed.

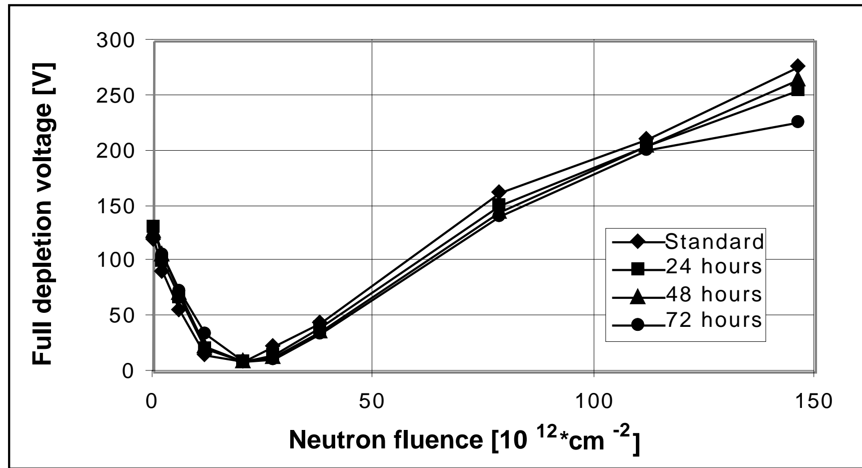


Figure 2: Dependence of full-depletion voltage on the irradiation neutron fluence.

3.3 Annealing

The detectors were heated to 60 and 80°C in order to emulate moderate- and long- term annealing processes [10]. Full-depletion voltage as a function of equivalent time periods at room temperature (20°C) from one day up to ~ six years is shown in Fig. 3. A decrease of the full-depletion voltage indicating a decrease in effective charge density in the depletion region is observed during the first ~ 20 days. Since the decrease of full- depletion voltage is favourable for the detector operation, it is referred to as 'beneficial annealing'.

After the equivalent time of ~ 30 days at room temperature the reverse annealing becomes dominant and remains dominant up to the longest tested time period.

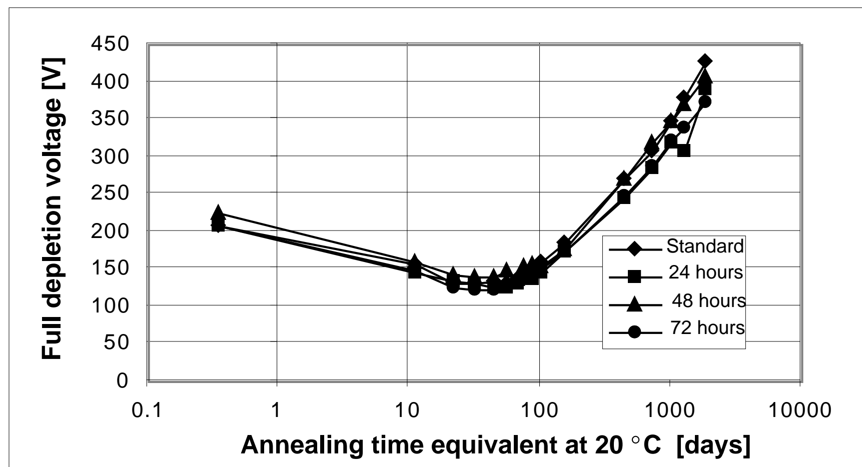


Figure 3: Influence of annealing on full-depletion voltage. The annealing process has been accelerated by 60 and 80°C heating [10].

3.4 Reverse current

For detectors irradiated up to ~ 8×10^{13} cm^{-2}, the dependence of the current on the square root of the voltage before full depletion is practically linear, indicating the dominance of the generation current mechanism in the depleted region. Above the

full- depletion voltage the current remains nearly constant with bias voltage, indicating no significant additional current mechanisms. In highly irradiated detectors, the current–voltage characteristics are more complex, implying the presence of other dominant current mechanisms. The reverse current at full-depletion voltage increases linearly with the fluence according to

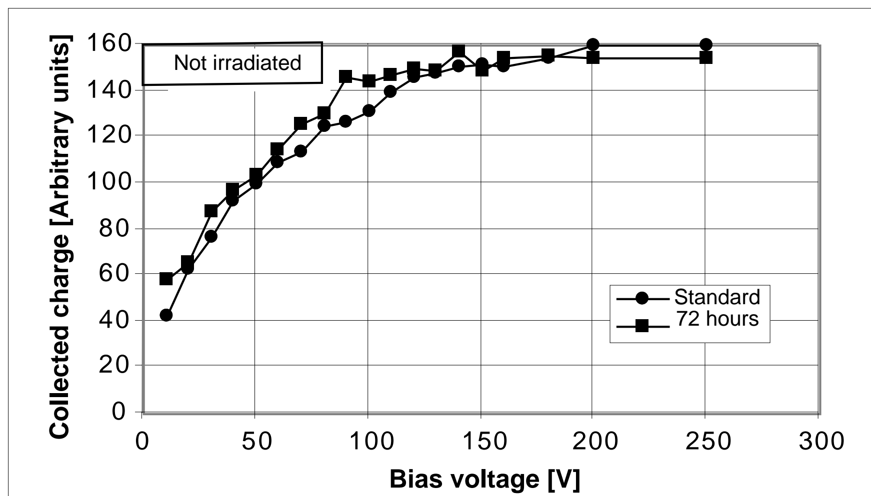
$$I_{\text{vol}} = I_{\phi 0} + \alpha \cdot \phi \ , \qquad (2)$$

where ϕ is the particle fluence, I_{vol} is the volume current in [A/cm^3], α is the reverse-current damage coefficient and $I_{\phi 0}$ is the current at zero fluence. The α coefficient at the end of the beneficial annealing has been found to be ~ 2.4×10^{-17} [A/cm], independent of the concentration of oxygen.

3.5 Charge collection and minority carrier lifetime

Introduction of deep levels, responsible for the resistivity increase, results also in signal charge trapping. Charge collection efficiencies for MIPs for non-irradiated and irradiated detectors are presented in Fig. 4. The dependence of the collected charge on bias voltage due to variations in space-charge density has been observed, however no significant differences have been found between oxygen-diffused and standard FZ silicon.

The lifetime of holes has been measured by the reverse recovery method [6]. For non-irradiated detectors processed from standard material the lifetime has been evaluated to be ~ 40 μs, almost a factor of two higher than for detectors fabricated from oxygen- enriched silicon. However, the lifetime drastically drops with fluence and the difference practically disappears after ~ 2×10^{13} cm^{-2}, at which point the lifetime is ~ 0.5 μs.



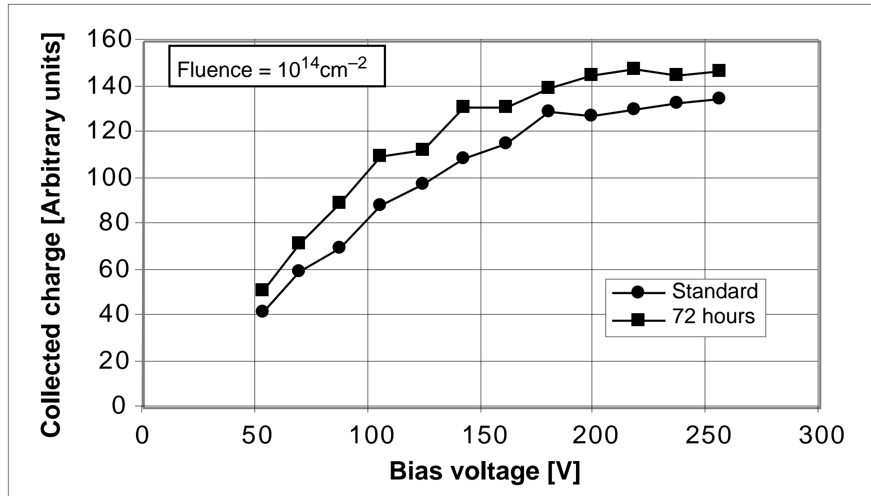


Figure 4: Charge collection for incident Minimum Ionizing Particles (MIPs) in standard and oxygen-diffused detectors. (a) Non-irradiated detectors, (b) After a neutron fluence of 1×10^{14} [cm^{-2}].

4 CONCLUSIONS

Oxygen diffusion from SiO_2 into n-type FZ high-resistivity silicon has been found to slightly reduce the material's resistivity. No significant influence of oxygen introduced by this technique on radiation hardness has been found. However, infrared spectroscopy measurements performed by ITME [4] indicate that most of the oxygen atoms were not interstitial, as would be desired for radiation hardness improvement [1, 2]. Therefore, an additional experiment is currently being prepared for analysis of radiation hardness of detectors fabricated from silicon enriched with interstitial oxygen.

Acknowledgments

We wish to thank Prof. Marko Mikuz and his team from Ljubljana University in Slovenia for their help in irradiating the samples. We thank Prof. Yael Nemirovsky and Dr. Camille Cohen from Technion in Israel for performing preliminary tests of oxygen diffusion. We also wish to thank Maciej Wegrzecki and Wojtek Slysz from ITE for the fast oxygen diffusion and fabrication of the detectors.

References

[1] B.C. MacEvoy, G. Hall, K. Gill, 'Defect evolution in irradiated silicon detector material', Nucl. Instrum. Methods A374 (1996) 12.

[2] M. Moll, H. Feick, E. Fretwurst, G. Lindstrom, C. Schutze, 'Comparison of defects produced by fast neutrons and ^{60}Co-gammas in high resistivity silicon detectors using deep-level transient spectroscopy', Nucl. Instrum. Methods A388 (1997) 335.

[3] Z. Li, W. Chen, L. Dou, H.W. Kraner, C.J. Li, G. Lindstrom 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 oxidation processes’, IEEE Trans. Nucl. Sci. 42 (1995) 219.

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

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

[6] S.M. Sze, ‘Physics of semiconductor devices’, Wiley-Interscience Publication, second edition, 1981. (Wiley, New York, 1981), p 868.

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

[8] M. Mikuz, ‘Time development and flux dependence of neutron irradiation induced defects in silicon pad detectors’, submitted to NIM proceedings of the 2nd International Conference on Radiation Effects on Semiconductor Materials, Detectors and Devices, Florence, 1998.

[9] EVANS EUROPA, Brunel University, Uxbridge, Middlesex UB8 3PH, UK.

[10] E. Fretwurst, H. Feick, M. Glaser, C. Gossling, E.H.M. Heijne, A. Hess, F. Lemeilleur, G. Lindstrom, K.H. Mahlmann, A. Rolf, T. Schulz and C. Soave, ‘Reverse annealing of the effective impurity concentration and long term operational scenario for silicon detectors in future collider experiments’, Nucl. Instrum. Methods A342 (1994) 119.