STATUS OF THE RD48/ROSE COLLABORATION

S. J. Watts, Brunel University, Uxbridge, UB8 3PH, UK. (email: Stephen.Watts@brunel.ac.uk)

Abstract

The status of the RD48 or ROSE (R&d On Silicon for future Experiments) Collaboration is described.

1. INTRODUCTION

This paper describes the work of many groups working within the RD48 or ROSE Collaboration with the specific objective of defect engineering more radiation tolerant silicon detectors [1,2]. Defect engineering involves the deliberate addition of impurities to silicon in order to effect the formation of electrically active defect centres and thus control the macroscopic parameters of devices. The key ingredients to change are oxygen and carbon. Oxygen and carbon capture silicon vacancies and interstitials respectively. The carbon is converted from a substitutional to an interstitial position which is mobile at room temperature. It eventually forms stable defects with oxygen and substitutional carbon. Diffusing silicon interstitials and vacancies escape from a region of silicon where an intense concentration of Frenkel pairs are produced by a Primary Knock-On Atom (PKA). The PKA is produced by the incident radiation. Vacancies can react with one another to form multivacancy defects. This leads to clustering of intrinsic defects around the PKA production point. This so-called “cluster” region controls many of the electrical parameters of irradiated silicon.

Various types of silicon have been evaluated with resistivities above 500 ohm cm. These are high resistivity epitaxial, FZ Si-Ge, FZ Si-Tin, carbonated FZ and oxygenated FZ. Highly oxygenated FZ has been produced using a "jet" technique by ITME in Poland - this involves a quartz ring plus oxygen gas jet around the float-zone. Oxygen concentrations of a few 10^{17} cm^{-3} are possible with this method. A key new technique is to diffuse oxygen into silicon wafers at high temperature – diffused oxygenated float zone (DOFZ), ref. [3]. Oxygen concentrations of a few 10^{17} cm^{-3} are possible. Moreover, this technique can be used on any wafer and can be performed by the detector manufacturer. Results with this material are identical to the jet oxygenated float zone. Note that the saturation oxygen concentration is $\sim 10^{18}$ cm^{-3}. Such concentrations are found in CZ material. However, the maximum resistivity of such material is about 100 ohm cm. Moreover, problems with thermal donors occur in CZ material. Thermal donor problems do not occur in DOFZ. The thermal donor density depends on the third power of oxygen concentration. Processing temperatures around 450 °C should be avoided [4].

2. MACROSCOPIC EFFECTS

Several macroscopic effects are seen in high-resistivity diodes following irradiation by MeV neutrons. Similar effects are also seen following GeV proton and pion irradiation which also create cluster type damage. Macroscopic changes **usually** scale with the Non-Ionising Energy Loss (NIEL). This has been calculated and can be used to relate the damage caused by particles of different types and energies. Thus, one needs only to refer to an equivalent 1 MeV neutron fluence. A compilation of recommended NIEL values to use for various particles over a wide range of energies is given in reference [1]. The various macroscopic effects seen in neutron irradiated silicon are described in ref. [5] together with a discussion of the complex room temperature annealing behaviour. Briefly, four effects are seen;

- The leakage current increases.
- N-type silicon behaves effectively like p-type material after an “inversion” fluence which is approximately 20 times the starting concentration. The effective doping, and thus depletion voltage then increases linearily with fluence. This change is described by a parameter called β. This ultimately limits the detector lifetime. A low β gives a longer operational lifetime.
- The space charge becomes increasing negative for a device that is left at room temperature after irradiation. This is called reverse annealing and can be inhibited by cooling below zero ^{0}C.
- The charge collection efficiency (CCE) degrades for fluences of several 10^{14} 1 MeV neutrons cm^{-2} due to charge trapping. The CCE is dependent on the space charge, voltage and temperature so that comparisons between various results must be made with care.

3. KEY NEW RESULTS

The leakage parameter, α, has been found to be material independent, [4]. Defect clusters are the main microscopic cause of the leakage current. The leakage current scales with NIEL and is a very reliable parameter for dosimetry and intercalibration of various radiation sources.

The one radiation parameter that can be altered and controlled, is the β parameter. This parameter for various substrates is shown in Table 1. Note that this parameter scales with NIEL for standard material. It does **not** for oxygenated and carbonated substrates that have been irradiated by charged hadrons. The fluence is a 1 MeV neutron equivalent and the leakage current was used to intercalibrate between the various radiation sources. DOFZ material has a lower β after irradiation by charged hadrons compared to standard FZ. Since the radiation field closest to the beam at the LHC is dominated by charged hadrons, DOFZ material is an exciting prospect for silicon detectors.

Table 1: The β parameter in various substrates, [6].

Material	β (cm^{-1}) Standard FZ	β (cm^{-1}) Oxygenated FZ
1 MeV Neutrons (Ljubljana)	**0.03**	**0.022**
24 GeV/c protons (CERN)	**0.03**	**0.010**
192 MeV pions (PSI)	**0.03**	**0.010**

The β parameter for charged hadron irradiation has been confirmed for DOFZ material produced by SGS Thomson, Micron Semiconductor, SINTEF, CIS, and ITE. A large number of diodes have been processed with different diffusion times, furnaces, crystal orientation and resistivities and then irradiated in order to optimise the DOFZ procedure. No significant effects have been seen. A thermal treatment at 1150 °C for 16 hours is sufficient to achieve the low β values shown in Table 1.

The physical explanation for the violation of the NIEL hypothesis in oxygenated material is now understood. Charged particles produce significantly more low energy PKA's. These do not produce clusters and the resultant isolated vacancy/interstitial pairs then lead to impurity related defects. Macroscopic parameters that are sensitive to these defects are therefore dependent on impurity concentrations. The leakage current is only dependent on clusters and is not sensitive to impurity levels. It is thought likely that the divacancy-oxygen defect is responsible for a large fraction of the β parameter. High oxygen concentrations inhibit the production of this defect. Recent microscopic measurements confirm that charged particles produce about twice the number of diffusing vacancies compared to neutrons when fluences are normalised using NIEL [7].

The lower β in DOFZ material has allowed reverse annealing data to be obtained for very heavily irradiated detectors. The damage factor for this process is seen to saturate for fluences above 6 10^{14} cm^{-2}; this is probably not material dependent. The time constant for this process is a factor 1.5 higher in DOFZ material; this is a preliminary result and needs further study. The increased time constant provides an additional safety factor for silicon detectors at the LHC.

Charge collection efficiency versus voltage data from diodes are consistent with depletion voltage information obtained using CV measurements. Data from strip detectors processed on DOFZ material will be available shortly.

4. OUTLOOK

The DOFZ technology has now been transferred to several detector manufacturers. Results from all manufacturers show improved hardness of DOFZ silicon diodes when irradiated with charged hadrons. Full scale prototype LHC microstrip detectors have been processed on DOFZ by both the CMS and ATLAS Collaborations. Irradiation results will be available shortly. Some oxygenated detectors will be installed in the HERA-B experiment next year. As in the past, experience in a real experiment will prove to be the ultimate test of a new technique. The violation of the NIEL scaling for DOFZ material irradiated by charged hadrons is a timely reminder of the danger of accepting useful hypotheses as dogma before the underlying physics is fully understood.

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6. REFERENCES

1. RD48 Status Report, CERN/LHCC 97-39, June 1997.
2. RD48 Status Report, CERN/LHCC 98-39, Oct. 1998.
3. G. Casse. Introduction of high oxygen concentrations into silicon wafers by high temperature diffusion, ROSE Internal Note, ROSE/TN/99-1, 1999.
4. M. Moll, Ph. D Thesis, University of Hamburg, September 1999.
5. S. J. Watts, LEB 1998 Workshop, Rome 1998.
6. A. Ruzin et al., 1st International Workshop on Defect Engineering of Advanced Semiconductor Devices, Santorini, April 1999.
7. E. Fretwurst et al., 1st International Workshop on Defect Engineering of Advanced Semiconductor Devices, Santorini, April 1999.