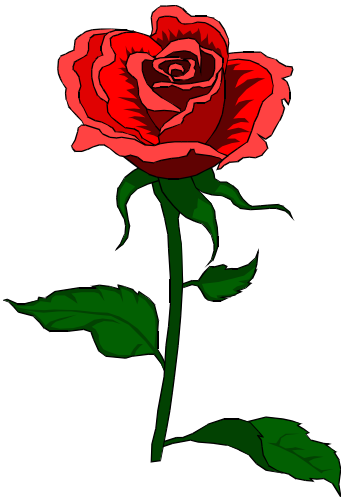

3rd ROSE Workshop on Radiation Hardening of Silicon Detectors

DESY Hamburg

12-14 February, 1998

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Scope

The ROSE / CERN RD48 Collaboration consists of international groups working on detectors for particle physics experiments at the LHC. In addition, the Collaboration benefits from the very valuable input of solid state physicists and the expertise of silicon manufacturers. The Collaboration formed following the First Workshop on Radiation Hardening of Silicon Detectors, held at CERN in October 1995. The proposal was approved by the LHCC in June 1996. The second Workshop was held at CERN in February 1997.

Meanwhile the Collaboration has presented its first status report to the LHCC (CERN/LHCC 97-39, July 1997). In view of the close relation of RD48is work to electronics, the LHCC decided to refer the project to the LHC Electronics Board (LEB) for the setting of milestones for the 2nd year. During its meeting on 31st October 1997, following a ROSE presentation at the LHC Electronics Workshop at Imperial College, the LEB reviewed the RD48 Status Report and recommended the following milestones for the continuation of the project (to be reported back by August 1998):

- decide on the processing options for epitaxial and float-zone silicon.
- evaluate hardness of detectors using highly oxygenated float-zone.
- evaluate hardness of Si-tin, and if promising clarify production possibilities.
- take active steps to raise awareness of RD48 results in the experiments by organizing a workshop in the first quarter of 1998, and establish, together with the experiments, recommendations on materials (raw material, resistivity, and qualification procedures) and detector processing.

In this workshop, the problems to be solved in order to reach the above milestones will be the subject of about 40 talks and a few dedicated round table discussions. The wide range of activities necessary to accomplish the goals of the Collaboration is reflected by the diversity of the contributions announced for this meeting. In the program outline we find details on the silicon crystal growth and characterisation, investigations into macroscopic damage effects on silicon detectors manufactured from various materials, studies on defect levels using a multitude of microscopic techniques, and even evaluations of the survivability of silicon sensors within LHC experiments. Moreover, we are looking forward to discuss the most recent results which have been obtained by the participants just in time with the workshop. It is thus anticipated that the meeting will enable the Collaboration to make a great progress in the understanding of the damage effects and consequently allow for even more valuable recommendations to the LHC experiments.

Material Growth, Analysis and Processing

Status of silicon material and detector production

Francois Lemeilleur, CERN EP, Switzerland

After a recall of the detectors processed in planar and mesa technologies from FZ and epitaxial crystals and already tested by various ROSE collaboration groups, the progress on the actual silicon production programme will be reported.

Highly oxygenated silicon with the FZ quartz ring method has been produced with a resistivity of 500 Ohm cm and development is underway to achieve higher resistivity and oxygen concentration. High temperature diffusion of oxygen in the bulk of standard FZ wafers has been achieved. Single planar diodes are being processed from these materials and from available wafers with different oxygen concentrations.A programme for addition of tin in silicon is underway.

Characterisation of ITME-Silicon for detectors

Elzbieta Nossarzewska-Orlowska, ITME, Warsaw, Poland

Average oxygen concentration in epitaxial layer deposited on CZ substrate was measured by FTIR method and a value of 1.5E16 cm^{-3} was obtained for 300 μm thick layer.

The oxygen concentration about 2E17 cm^{-3} in FZ crystals was reached by gas doping.

Mesa diodes (marked by CERN as: N-type- I1, I11, I21, I31 and P-type -I1P, I11P, I21P, I31P) made on ITME epitaxial wafers were measured by spreading resistance(SR) and C-DLTS methods.

Resistivity profiles on N-type diodes show nonuniform distribution of donors concentration in depth. After irradiation to 3.4E12 proton/cm^2 the resistivity is higher than in starting epitaxial layer but still nonuniform; after irradiation to 5.8E13 proton/cm^2 the resistivity is at the level of 4E4 ohmcm in all volume, N-type (staining test).

C-DLTS were measured on mesa diodes in the region close to the substrate - epilayer interface. In non-irradiated N-type diodes three deep levels at 0.3 eV,

~0.4 eV and dominating ~0.52 eV are seen on the DLTS spectrum. After irradiation only I1 diodes have been measured: I1 - 8 irradiated to 3.4E12 proton/cm^2 and I1-5 irradiated to 5.8E13 proton/cm^2 (June 1997). A deep level at 0.17eV and two peaks at about 0.4 eV are seen in the both samples, but in the sample I1-8 the traps revealed in unirradiated diode are also observed.

In P-type mesa diodes before irradiation the resistivity is lower than in starting epi layer and resistivity profiles are flat. After irradiation to 6E13 proton/cm^2 the resistivity is higher than in starting epilayer and the profile is also flat.

Before irradiation three hole traps are observed : 0.19 eV, ~0.3 eV and ~0.4 eV.

After irradiation to 6e13 proton/cm^2 diodes I1P -3 and I11P-3 were measured. The DLTS peaks are at ~ 0.3 eV, ~ 0.4eV and deep level at ~0.6 eV.

First attempt to measure deep levels in irradiated mesa diode I31-4 (N-type) by PhotoInduced Transient Spectroscopy was made. The levels at 0.17 eV and at ~0.4 eV are observed.

Impurity, Resistivity, Noise and Crystallography measurements of processed and irradiated FZ silicon

Arie Ruzin, CERN EP, Switzerland

Concentrations of impurities measured by Secondary Ion Mass Spectroscopy (SIMS) in processed float zone material are presented. In mesa structure, profiles of Phosphorus and Boron were studied as well as profiles of Oxygen and Carbon. First results of Oxygen diffusion into float zone silicon from SiO2 layer are described. The SIMS profiles are corroborated by depth resistivity profiles measured with the spreading resistance technique. Comparison of I-V characteristics with the guard ring biased and floating is presented for irradiated as well as non-irradiated detectors. The different values of alpha achieved with the two measurement set-ups are compared. Noise current spectral densities of irradiated and non-irradiated detectors are presented for the first time. Preliminary results of crystallographic characterization of irradiated float zone silicon material are exhibited.

Macroscopic Measurements: Dependence on Experimental Parameters, Material and Processing

Influence of Oxygen concentration on radiation hardness of Silicon Detectors

Gianluigi Casse, CERN EP, Switzerland

Comparison between planar and Mesa processed detectors. Electrical properties of the detectors have been studied, before and after irradiation, in order to find the correlation with the material type, the fabrication process and the radiation hardness. Role of oxygen as possible candidate for the rad-hard improvement in Mesa processed detectors. Preliminary results of 1 MeV neutron irradiation of planar diodes manufactured from high temperature oxygen diffused FZ silicon wafers.

Electrical characterisation of standard and oxygenated irradiated ROSE diodes

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In this work we report preliminary results from electrical characterization of bulk n-doped silicon samples and p+ n diodes. Bulk samples, oxygenated (7 10^15 atoms/cm^3) and not, have been characterized with Hall mobility and conductivity measurements as a function of temperature, before and after irradiation. p+n diodes have been characterized with C-V and leakage current measurements as a function of temperature. Investigated samples have been grown by FZ technique in Polovodice (Prague) and have been irradiated with protons at CERN facilities (F= 4 10^11 - 10^14 protons/cm^2 s). Aim of this work is to understand the role played by oxygen atoms in limiting radiation damage. Carrier concentration, n, has been evaluated by conductivity and Hall mobility measurements; plots of n as a function of the inverse of temperature, for samples irradiated (F= 4 10^12 protons/cm^2 s) and not, show a shift of the Fermi level, Ef, towards midgap in irradiated samples. Such a shift is much higher in standard sample (Ec-Ef=0.43 eV) than in oxygenated ones (Ec-Ef=0.34 eV). C-V measurements on irradiated diodes (F = 10^14 protons/cm^2 s) show a decrease of the effective concentration Neff with respect to

unirradiated samples and the relative decrease is lower in oxygenated sample. Leakage current has been also measured as a function of temperature. It increases of about 4 orders of magnitude in irradiated samples and this independently of oxygen content.

Preliminary results from the neutron irradiation at the Ljubljana reactor facilities

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Abstract

A large number of high-resistivity silicon diodes were irradiated with fast neutrons from the TRIGA experimental nuclear reactor in Ljubljana. Dose rate, fluence, annealing temperature and oxygen concentration influence on the defect creation and developement were studied. $|N_{eff}|$ was followed by C/V measurements even on-line during irradiation. Irradiation and annealing behaviour was studied in a controlled temperature environment.

IRRADIATION FACILITY

Diodes were irradiated at the TRIGA experimental nuclear reactor. Most of the samples were irradiated at the edge of the reactor core with the damage factor relative to 1 MeV neutrons equal to 0.92 ± 0.05. Varying reactor power, fluxes from about 10^8 to 2×10^{12} n/cm^{2}s can be obtained in normal operation mode. In pulsed mode as much as 10^{14}n/cm^2 in 20ms can be achieved. Samples are inserted through an Al tube which limits the sample size to 20×50 mm^2.

The rest of the samples were irradiated in the irradiation chamber. This is placed outside the reactor vessel. Thermal neutrons induce fission in a ^{2}35U plate, providing a fast neutron flux of about 5×10^8 n/cm^{2}s with a damage factor relative to 1MeV neutorns equal to 1 ± 0.05. At this site samples as large as $\approx20\times15$ cm^2 can be irradiated.

IRRADIATION SET-UP

Both set-ups provide controlled sample cooling. At the first irradiation site (at the core edge) liquid cooling is used providing a minimum stable temperature of about 0^{o}C. In the irradiation chamber Peltier elements are used

and sample temperatures as low as -25°C can be obtained. In both irradiation sites sample biasing and C/V and I/V measurement during and after irradiation is provided. WENZEL high voltage power supply is used for sample biasing. HP4263B LCP meter is used for C/V and KEITHLEY 617 for I/V measurements.

With described set-ups deffect creation and short term annealing constants can be measured as a function of temperature.

RESULTS

15 samples irradiated under different irradiation conditions were used in the analysis. 11 of them were 1 $\times$ 1 cm ^{2} litografy processed float-zone diodes with 2 or 3 guard rings. The remaining 4 were 5 $\times$ 5 mm^2 diodes with no guard ring, produced by MESA process, two of them being from oxygen enriched wafers.

Dose rate effect

9 of the samples were irradiated with 2×10^9n/cm^2, two with 2×10^{12}n/cm^{2}s, one with 2×10^8n/cm^{2}s, 2×10^{10}n/cm^{2}s, 2×10^{11}n/cm^{2}s each, and one in pulsed mode. In this way the flux was varied over 7 orders of magnitude. No significant differences corelated to a dose rate effect was found.

Fluence effect

Regarding the total fluence samples can be divided into three major groupes. Two were irradiated to about 10^{13}n/cm^2, eight to about 5×10^{13}n/cm^2 and five to about 10^{14}n/cm^2. Samples were (fully?) reverse annealed at 60°C. Φ^{-1} dependence of the reverse annealing constant k_y was checked.

Temperature effect on short term annealing

Samples were iradiated and then stored for about a week at different temperatures (15°C, 5°C, 0°C -10°C). Short term annealing (hours) time constants were measured and activation energies estimated from the Arhenius plot.

Oxygen effect

Pairs of oxygen enriched and normal MESA processed sample were irradiated at 5°C and 15°C, all to 5×10^{13}n/cm^2 with 2×10^{13}n/cm^{2}s. Oxygen enriched samples were compared to normal MESA ones and litography processed samples. While normal MESA samples did not show significantly different behaviour than litography ones, preliminary results of the annealing and reverse annealing of the oxygen enriched seem to show a significant discrepancy.

Macroscopic characterization of the irradiated ROSE diodes

Lesley Jane Beattie, Lancaster University, UK

A study was made of the changes to macroscopic properties of ROSE diodes made of standard, oxygenated and nitrogenated silicon after irradiation by neutrons to fluences in the range (1-3)x10^14 cm^-2. Diodes of dimension 5mm x 5mm x 300um were measured for both capacitance-voltage and current-voltage characterstics before and after irradiation. Irradiations were performed at ISIS (RAL) at room temperature without bias.

Using elevated temperature annealing with 1 day at 295K equivalent to 2 hours at 310+-1K, C-V and I-V were monitored day by day until all beneficial annealing had occurred, and we noted that typical time for this to occur was between 4 and 10 days.

The change in the depletion voltage vs. fluence follows a usual nearly linear behaviour. All the data agree with expectations. No significant difference between standard and non-standard materials was observed.

Current through the bulk of the diode was initially no more than a few tens of uA, but after irradiation and subsequent beneficial annealing had increased significantly. Maximum current during measurements was limited to 200uA. Current density is seen to increase linearly with fluence.

Reverse annealing was allowed up to 200 days or more for 4 of the diodes, using elevated temperature annealing to advance in steps of 25 and 50 days. The results are compared with the model suggested by Hamburg group.

Defect analysis of ROSE detectors made of different materials for radiation hardness

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Since 2 years an intensive effort has been made on the radiation hardness studies of detectors from epitaxial Si. On the 2nd ROSE workshop, the more radiation hardness of epitaxial grown detectors has been presented. Low resistivity MACOM epitaxial test structures came out to be more radiation hard in terms of effective doping concentration in the space charge region (N_{eff}) than standard FZ detectors [1,2]. However high resistivity MACOM and ITME epitaxial grown Si detectors do not show the same behavior.

A more detailed study has now performed in order to understand the origin of these differences in epitaxial grown materials. Epitaxial detectors with different resistivities have been compared with standard FZ detectors of comparable resistivities. The data of N_{eff} of these detectors as a function of fluences, as well as the data of N_{eff} equivalent RT annealing behavior, will be presented.

For highly irradiated samples, the full depletion voltage has been determined by the Transient Current Technique (TCT).

Initial data show that the radiation induced changes in the effective doping concentration is mainly caused by the effect of compensation due to deep acceptors. The effect of the donor removal may not be a real physical effect but rather a convenient explanation of this compensation effect at low fluences in high resistivity silicon detectors.

I-DLTS have been performed on various highly irradiated ($6\ 10^{14}$) epitaxial detectors and compared with standard FZ silicon detectors [3]. Comparisons have also been made among samples irradiated by neutrons and gamma.

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Some Preliminary Studies of Irradiated p-type Structures on Epitaxial and Float Zone Material

Moshe Hanlon, Liverpool University, UK

Charge collection efficiency of silicon detectors measured with heavy charged particles

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Long range alpha particles (Emax 8.8 MeV) and protons (Emax 2.5 MeV) have been used to study the charge collection efficiency of non-irradiated and irradiated silicon detectors. The detectors, 290 micrometers thick, were manufactured by Canberra from crystals produced by Wacker. The irradiated detectors were exposed to proton fluences from 5x10**12 up to 2.2x10**14/cm**2. The detectors wereilluminated on the front side and rear side at different bias voltages. The particles used for illumination, having well defined ranges and ionization losses, allowed the scanning of the charge collection across the whole detector thickness. Electrode and dead layer thicknesses were determined. The charges collected when the detector is illuminated on the rear side, exhibit a different behaviour as a function of voltage before and after inversion.

Systematic Effects in Measurements of the Depletion Voltage

Alex Chilingarov, Lancaster University, UK

The depletion voltage in non-irradiated Si detectors can be measured by many different methods all of them giving very similar results. For irradiated detectors all these methods produce different answers and this difference grows with fluence. The results of a systematic study made with the aim to understand the origin of these differences and to reconcile them by a common interpretation are presented.

The methods analysed are: C-V, I-V, Charge Collection Efficiency for a) minimum ionising particles and b) for alpha-particles illuminating the ohmic side of the detector.

The systematic differences in the depletion voltage measured by these methods are discussed as well as some possibilities for their explanations. The complexity of heavily irradiated Si behaviour leads to the conclusion that probably the whole notion of depletion voltage needs to be revised before a correct way of measuring it can be defined.

Microscopic Analysis of Defects

Influence of the oxygen concentration on the radiation hardness of silicon detectors

Michael Moll, Universität Hamburg, Germany

Since up to now detector grade FZ silicon with a high oxygen content was not available, the radiation hardness of silicon detectors was studied on Czochralski grown silicon which due to its growth in a silica crucible contains a high oxygen concentration. Unfortunately there is no uncompensated CZ silicon with a resistivity higher than 100ohmcm. Therefore also low resistiviy FZ silicon had to be investigated in this study for comparison.

The macroscopic damage parameters of Schottky-diodes produced on 140ohmcm Cz ([Oi]=1e18cm^{-3}) and 130ohmcm Fz ([Oi] ~1e16cm^{-3}) were monitored during isothermal heat treatments at 60°C following neutron irradiations with fluences of up to 1e15 cm^{-2}. While for the leakage current no dependence on the oxygen concentration could be found, the effective doping concentration was strongly influenced. For the FZ silicon the type inversion took place at a fluence of 5e14cm^{-2} while the CZ silicon was still n-type at 8e14cm^{-2}. Furthermore it was found that the reverse annealing amplitude for the CZ samples was reduced by a factor of 2 compared to the amplitudes measured on high resistivity FZ silicon.

Combining DLTS measurements with a simple defect kinetics model, it becomes obvious that the improved radiation hardness in terms of the higher inversion fluence is at least partly due to the process (V+O = VO), which suppresses the donor removal (V+P = VP) efficiently in CZ silicon.

In conclusion a high oxygen concentration reduces the radiation induced change of the depletion voltage and therefore improves the radiation hardness of silicon detectors.

Investigation of Radiation Hardness of Detectors Fabricated on Wafers with Thick Epitaxial Grown Layers

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Different approaches to improve radiation hardness of silicon detectors and minimize reverse annealing effect have been tried recently. This work deals with a new approach, which considers epitaxial layers as a starting material for detector fabrication. To estimate their possible advantages, detectors processed from bulk silicon with increased concentration of oxygen were also investigated in parallel. The main idea of this comparison is based on the hypothesis that accumulation in time of additional negative charges (reverse annealing effect of space charge concentration N_{eff}) occurs due to the formation of deep acceptors by vacancies released from clusters. A high initial concentration of defects in epitaxial grown layers or high oxygen concentration in the silicon bulk is suggested to be beneficial to inhibit this process because the epi-defects and/or oxygen atoms can capture the released vacancies and lead to their annihilation with lattice defects and/or formation of the A-centers (V-O) rather than divacancies V-V^- or the V_n-O complexes.

. **Experimental**

Detectors from epitaxial Si were manufactured as bevelled etched Shottky diodes with metal contacts or planar detectors.

Detectors from bulk silicon were produced from Wacker Si and Si manufactured by Polovodice, Czeck Republic. Excessive oxygen concentration was introduced into Wacker Si by wet oxidation, or directly into the silicon ingots of Polovodice Si during crystal pulling. Epitaxial layers of n and p-type with thickness ranging from 100 to 200 μm were grown with a resistivity (ρ) of a few kΩ·cm by ITME, or with a resistivity of 500 Ω·cm by MACOM, USA, on wafers from low resistivity (50 Ω–cm) CZ Si. Detailed descriptions of the detectors used in this study are listed in Table I.

C-V and I-V measurements, TCT technique, and C-DLTS/I/DLTS spectra measurements were used for the investigation of non-irradiated detectors and detectors irradiated by protons or fast neutrons. Elevated temperature annealing (ETA) at T = 80°C was performed for planar detectors to stimulate reverse annealing.

Detectors under study			(Shottky diodes)	
Detector #	Epi-layer		Fluence	Radiation
	Type	Thickness [um]	[cm-2]	
I 21-B-6	n	150	0	no
I 21-P-B-12	p	150	0	no
I 31-P-B-12	p	200	0	no
I 21-B-9	n	150	1,50E+11	protons
I 21-P-B-15	p	150	1,50E+11	protons
I 31-P-B-14	p	200	1,50E+11	protons

Reference detectors		(bulk Si, 2kOhm-cm)		
Detector #	Material		Fluence	Radiation
Planar det	Type	Thickness, [um]		
P88-S-A-3-11	n	277	1,50E+11	protons
P81-C-A3-17	p*	300	1,00E+14	neutrons

Note: * - after type inversion under irradiation
Energy of protons Ep=24GeV
Energy of neutrons En=1MeV

Table I

2. Results

1. Thick (>100 μm) epitaxial high resistivity Si layers contain significant concentration (up to 10^{12} cm^{-3}) of defects with deep levels (Table 1) even before irradiation. Concentration of epitaxial defects increases superlinear with a thickness of as-grown layer.

2. Epitaxial defects act as sinks for radiation induced primary defects detectors at low fluences. This sinking or gettering effect is evinced by significantly low concentration of radiation induced defects in epitaxial base compared with that in control detector produced from bulk Si (Fig.1).

3. At high radiation fluence (10^{14} cm^{-2}) epitaxial defects are saturated by radiation defects, and a standard spectrum of radiation induced defects is detected. The net effective concentration in the space charge region equals $3 \cdot 10^{12}$ cm^{-3} after 3 months of room temperature storage followed by an ETA, and reveals similar annealing behavior for epitaxial silicon as compared to bulk silicon. The total concentration of N_{eff} is lower than the bulk value (which is in the order of 6 to 8 x10^{12} cm^{-3}) (Fig. 2). This is probably due in part to the fact that the initial resistivity of Epi-Si detectors are about five times lower than that of standard bulk detectors{1-2].

4. Detectors from standard and oxygenated bulk silicon do not show pronounced difference in their characteristics because an excessive concentration of oxygen is comparable with its concentration in standard Si. Still, full depletion voltage V_{FD} measured after the same time of room temperature annealing (RTA) was larger for standard Si. The rate of V_{FD} increase under ETA was similar for both standard and oxygenated Si.

5. The results show some advantages of epitaxial material for radiation harden detectors in the low radiation fluence range (Fig.2). More experiments are needed to investigate the main regularities of the effect observed and its development to the problem of radiation hardness of Si detectors.

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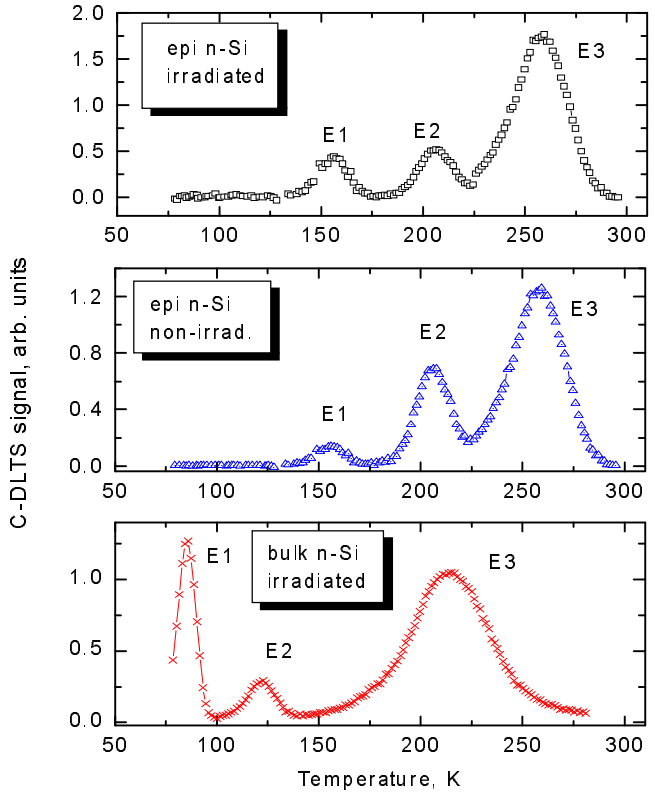

Figure 1 C-DLTS spectrum of lowly irradiated Epi-Si detector as compared to those of a non-irradiated Epi-Si detector and an irradiated bulk detector

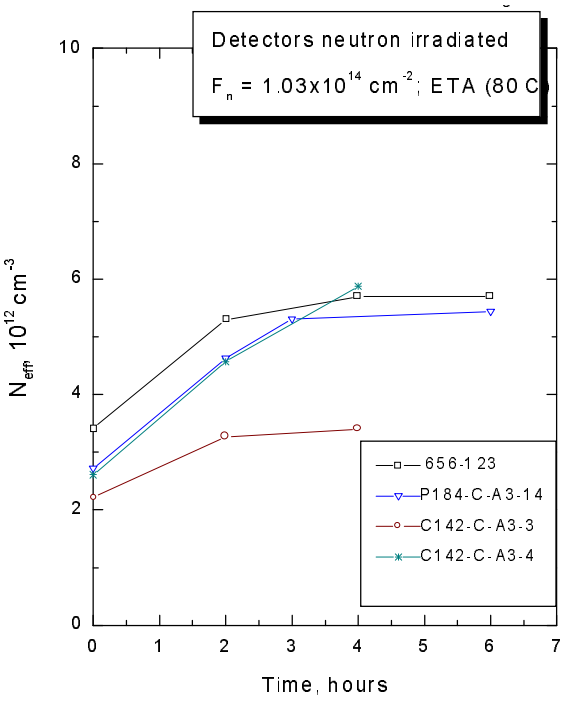

Figure 2 Reverse annealing behavior for Epi-Si detectors and control detectors

DLTS results on ROSE diodes

M. Ahmed, I. Bond, A. Holmes-Siedle, J. Matheson, M. Solanky, S. J. Watts

Brunel University, UK

The talk will discuss the following points:-

a) DLTS results for epitaxial diodes irriated at the CERN PS. Depth profiles and isochronal annealing data will be presented.

b) DLTS results for FZ diodes irradiated with low energy protons. These protons stopped at a depth of about 50 microns from the surface.

c) The annealing of defects in diodes will be discussed in terms of recent theoretical work on multi-vacancy defects. A possible explanation for reverse annealing will be proposed.

Forward characteristics and DLTS results on FZ ROSE material

Mita S. Solanky, Brunel University, UK

Part I - Further Study of the Forward Characteristics of Silicon Diodes

The talk will begin with a brief recap of the work presented at the previous Rose Collaboration Meeting. It will then go on to present new data taken at CERN of different types of material, including; Standard Float Zone, Oxygenated and Nitrogenated Material, Epitaxial Material and also p-type material. Forward characteristic data will show pre and post-irradiation measurements. The diodes were all irradiated using the CERN 24 GeV/c proton beam.

Further work using the KURATA simulation program will also be presented. This work shows simulations for three cases; 1) how deep acceptors introduced by the program affect the forward characteristic without changing the miniority carrier lifetime 2) changing only the minority carrier lifetime without including any deep acceptors. 3) changing the minority carrier lifetime and adding deep acceptors.

Results clearly show that the lifetime is the dominant factor in affecting the changes in the forward characteristic. However, there is also some contribution due to the deep acceptors. It can be concluded that silicon transforms from a lifetime-like material into a relaxation-like material at high fluences (~1e14 hadrons/cm2). This is shown by studying the ideality factor curves for both experimental and modelled data.

Part II - Systematic Investigation of Different Materials using DLTS

ROSE diodes proccessed by different manufacturers on different silicon material were collected and a systematic study of these diodes using DLTS is being carried out in order to show up any differences introduced due to processing techniques used. Diodes under test include both Float-Zone and Epitaxial material. This talk will present only the float zone data.

Diodes under test include standard float zone material, and material processed by Canberra, Sintef and Diotec who implemented the MESA process. For each type of material three samples were collected; 1) an unirradiated sample for control purposes 2) an irradiated sample (guarded) 3) an irradiated sample (without guard ring). Diodes were irradiated simultaneously to a dose of 1e11 protons/cm2.

Radiation Hardness and Microscopic Defect Investigation in "Exotic" Silicon with Excess Oxygen and Nitrogen

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Ioffe Physico-Technical Institute, Russian Academy of Sciences

Z. Li
Brookhaven National Laboratory

Improvement of radiation hardness of silicon detectors implies reduction of reverse annealing effect and increase of reliability of various semiconductor detectors in colliders. One of the technology trends dealing with this problem is impurity engineering. The aim of impurity engineering is to introduce the excessive contamination into the bulk of high resistivity silicon to affect the generation rate of the formation of defect complexes from primary defects. Recently a new approach using epitaxial silicon as a starting material for detector manufacturing has been developed.

Various silicon materials studied in PTI were represented by the characterization of three groups of detectors:

4. Detectors (# P...-S...) from bulk Si produced by Polovodice, with a resistivity ρ = 1÷2 kΩ·cm: standard and with oxygen concentration of $1.1 \cdot 10^{16}$ cm^{-3} (IR measurements);
5. Detectors (# P...-I...) from bulk Si with ρ = 4÷5 kΩ·cm produced by Polovodice: standard and with nitrogen concentration of $5 \cdot 10^{15}$ cm^{-3} (IR);
6. Detectors from epitaxial silicon of n and p-type conductivity (see the paper of Z.Li).

Each group contained non-irradiated detectors and detectors irradiated by proton fluence F_p of $1.5 \cdot 10^{11}$ and $1.1 \cdot 10^{14}$ cm^{-2}. Characterization techniques applied in this study include I-V, C-V and TCT measurements for depletion voltage determination, C-DLTS/I-DLTS for defect analysis. C-DLTS measurements were carried out for non-irradiated detectors or detectors irradiated to low proton fluence while I-DLTS technique was used for detectors irradiated by high fluence. Elevated temperature annealing (ETA) at T_{ann} = 80°C was applied to study reverse annealing.

Experimental results

1. Before irradiation (or as processed detectors), no thermal deep levels are induced in bulk high resistivity Si by heat treatment during detector manufacturing by SINTEF and ITE.
2. Significant concentration of deep levels was observed in the as-processed detectors manufactured from epitaxial grown Si. The defect spectrum is different for p- and n- epitaxial material.
3. Results of TCT measurements showed space charge sign inversion for detectors irradiated by $F_p = 1.1 \cdot 10^{14}$ p/cm^2. Dependence of the full depletion voltage V_{FD} on annealing time t (shown in Fig.1) tends to saturate to the value specific for each type of Si. Corresponding saturation values of N_{eff} show that the N_{eff} differences among them after irradiation are close to the

differences in N_{eff} values among starting materials. This effect implies that the change of N_{eff} is totally caused by the compensation of negatively charged deep acceptors in the space charge region, and that there is no donor removal effect[1].

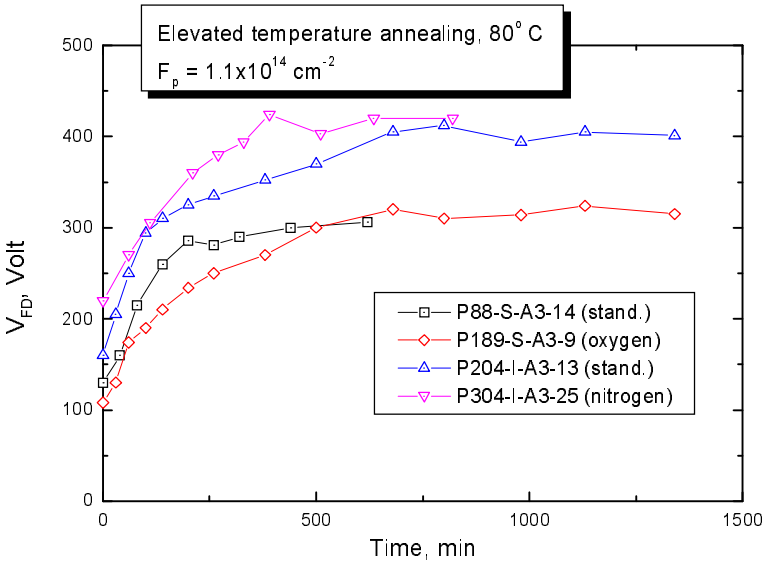

Fig.1. Full depletion voltage vs. annealing time for detectors from various types of silicon.

4. The fittings to the curves in Fig. 1 show that the N_{eff} reverse annealing effect is in fact a first order process, which confirms the early finding in ref.[2] in high irradiated silicon detectors.

5. As the excessive O and N concentrations in specially doped Si is rather small compared to standard Wacker silicon (e.g. only a factor of 3 larger for in [O], and comparable in [N]), the gettering effect radiation-induced defects by these impurities is not observed.

Simulation of deep level spectra

In this study, special attention has been paid to the analysis of C- and I-DLTS spectra, by precise simulation, to get more information on the radiation defect formation in silicon.

The simulation of deep level spectra was based on numerical modeling of charge carrier emission versus T according to Shockley-Read-Hall statistics without any simplification on the relation between concentration of shallow and deep levels. The procedure was performed using a spreadsheet of Microsoft Excel software for numerical calculation. Simulation of C-DLTS spectra based on the parameters derived from experimental spectra (from Arhenius plots of t1 as a function of the reciprocal of the DLTS peak temperature) showed that the shapes of simulated peaks were different from those for experimental ones in the range of DLTS peak assigned to VV^- (Fig.2). For detectors irradiated by low proton fluence good agreements were obtained by simulation using the parameters listed in Table 1 which were practically the same for both C-DLTS and I-DLTS spectra. The reduced energy and unreasonable small trapping crossection for the simulated DLTS peaks of V-V-becomes

stronger for detectors irradiated at higher fluence. The possible reason of this broadening and DLTS peak distortion may be cluster formation by high energy particles so that significant number of the defects (divacancies) is localized inside dense clusters. Interaction between defects inside crystal by distortion of lattice in the core of a cluster can affect detrapping time constant and therefore the position and shape of DLTS peak.

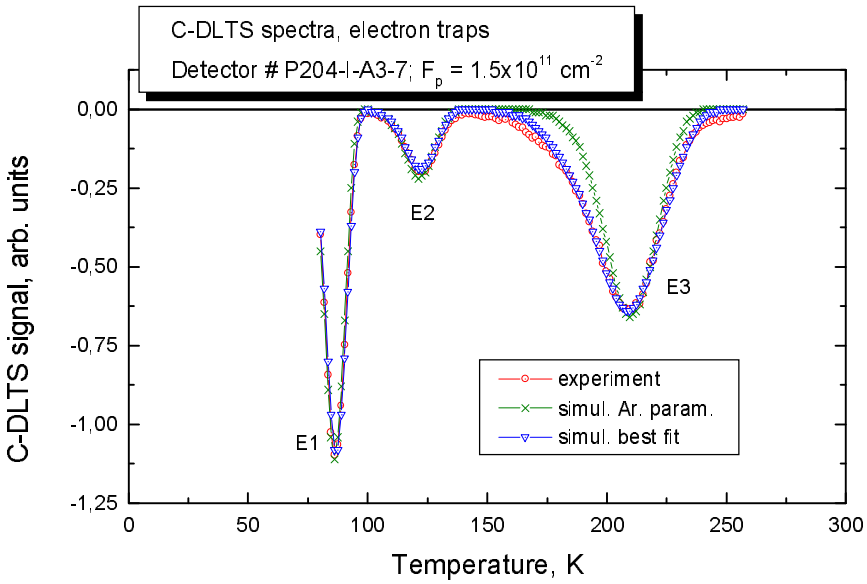

Fig. 2 Comparison of experimental and simulated C-DLTS spectra for detector irradiated at low proton fluence

References:

1. Z. Li, et al., BNL-64488, Presented at the 7th Pisa Meeting on Advanced Detectors, Elba, Italy, 25-31 May 1997, accepted by Nucl. Instrum. & Meth.
2. Z. Li, BNL-60273, IEEE Trans. Nucl. Sci. NS-42, No.4, 224(1995).

Radiation damage analysis on p-type silicon

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[2] University of Bucharest, Romania
[3] BNL, Upton, New York

P-type Hall samples and n^+p junctions have been irradiated with 1MeV neutrons in the fluence range from 10^{12} to $5x10^{14}cm^{-2}$. Two sets of Hall samples have been considered: p-type bulk produced at Stanford, with a thickness of 300μm, and p-type epitaxial silicon. In the latter samples an epilayer of 150μm is grown on a 600μm thick CZ substrate. The p-type detectors have been processed by Canberra from TOPSIL wafers 300μm thick with initial resistivity of 30kΩcm. Hall effect measurements have been performed on the bulk (b) and epitaxial (e) p-type samples in the temperature range from 15 to 35°C, to determine the resistivity (ρ) and the Hall coefficient (R_H).

ρ_e = 2Ωcm and ρ_b = 15kΩcm and positive Hall coefficients have been found at T=27°C before irradiation corresponding to free hole concentrations respectively of p_e= $6x10^{15}cm^{-3}$ and p_b=$7.6x10^{11}cm^{-3}$.

TSC analysis have been performed on the p-type detectors to relate the radiation induced defects with the change in resistivity observed after irradiation with Hall effect measurements.

Investigation of Trapping Levels in Standard, Nitrogenated and Oxygenated Si p-n Junctions Using the Optical Charging Spectroscopy and TSC

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The trapping levels induced in p-n Si junctions by 24 GeV proton irradiation were investigated. The junctions were manufactured in planar technology using different sorts of Polovodice Si wafers, namely standard, oxygenated (10^{16} oxygen/cm^3) and nitrogenated (10^{15} nitrogen/cm^3) Si. The resistivity was of 2.5 kΩcm for the standard and oxygenated Si and 5 kΩcm for the nitrogenated Si. The area of the manufactured p-n junctions was of 5x5 mm^2 and the thickness was about 300 μm. These samples were irradiated with five proton fluences ranging between 10^{12} and 10^{14} protons/cm^2. The samples were received from CERN on 15 May 1997 and their characterization was finished on 30 June 1997. Trap investigation was performed using Optical Charging Spectroscopy

(OCS) and Thermally Stimulated Currents (TSC) methods in the 90-300 K temperature range. Whenever was possible the fractional heating method was applied in order to compute the activation energy of the trapping levels using Arrhenius plots. In case of TSC spectra a deconvolution program was used considering a number of peaks equal with the number of peaks observed in the OCS spectra. The TSC measurements were performed in full depletion to be sure that all the trapped charge is collected at the electrodes. Some measurements were performed using lower reverse voltages (1.5 V) in order to increase the energetic resolution of the TSC spectra.

The OCS and TSC spectra show, in principle, the same structure, with the same peaks occurring at approximately the same temperatures no matter the Si used for p-n junction manufacturing. This can lead to the conclusion that the defects induced by proton irradiation are the same in all the samples.In Table I are synthesised the results concerning the trap parameters for the samples irradiated with the highest proton fluence.

Table I. Activation energy E_t, peak temperature T_m, trapping cross-section s_t and trap density N_t for the trapping levels observed in proton irradiated Si p-n junctions.

Trap parameter	**1**	**2**	**3**	**4**	**5**	**6**
E_t (eV)	**0.27**	**0.30**	**0.35**	**0.48**	**0.47**	**0.50**
T_m (K)	**120-122**	**134-135**	**152-153**	**166-169**	**177-179**	**188-190**
s_t (cm^2)	**10^{-16}**	**10^{-16}**	**10^{-16}**	**10^{-13} - 10^{-14}**	**10^{-14} - 10^{-15}**	**10^{-14} - 10^{-15}**
N_t (cm^{-3})	**10^{12}**	**10^{12}**	**10^{13}**	**10^{14}**	**$3x10^{13}$**	**$2x10^{13}$**

It was also observed that increasing the proton fluence the amplitude of the discharging current increases, especially in the case of the peak occurring at the 166-169 K. That imply a sharp increases of the trap density for fluences above 10^{13} protons/cm^2.

A scanning of the sample volume was performed using different wavelengths (0.4 - 0.975 μm) and performing illumination first from the p-side and then from the n-side. It was observed that at low injection levels (0.4 μm) the current peak associated with the discharging of the trap level having the activation energy of 0.48 eV is no longer occurring in the OCS spectra. This peak occurs only at high injection levels (0.7 - 0.975 μm). The current peak associated with the trapping level having the activation energy of 0.47 eV can be seen in the OCS spectra no matter the level of injection The analysis of these results lead as to the conclusion that the level occurring at about 166-169 K is an electron trap and that the level occurring around 178 K is probably a hole trap.

Dose dependence of the concentration of carriers in high resistivity Si irradiated by 24 GeV protons and properties of the detectors on its base

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[2]CERN, Geneva.

Silicon samples with specific resistivity ~2500 Ohm·cm with oxygen and without it before and after irradiation by 24 GeV protons till fluence 10^{14} p·cm^{-2} were investigated.

It was established, that the electron concentration decrease not only due to introduction the divacancies and E-center, by due to the cluster defects, which around by the space charge, till fluences of $8 \cdot 10^{12}$ p·cm^{-2}. At fluence of $\geq \cdot 8 \cdot 10^{12}$ p·cm^{-2} Fermi-level in clusters and in matrix silicon is the same and equal to (E_c – 0,5)eV in silicon with oxygen and equal to (E_c – 0,53)eV in silicon without oxygen. The rate of carrier removal was estimated as 0,35 cm^{-1} in silicon irradiation by 24 GeV protons. 24 GeV protons creates the cluster of defects with average radii of 330Å and energy of 480 KeV is lost on its creation. In silicon without oxygen were observed acceptor level (E_c – 0,49)eV and E-center level (E_c – 0,47)eV.

In silicon with oxygen we observed not only divacancy level (E_c – 0,42)eV and also effective level (E_c – 0,45)eV with rate carrier removal of 0,16 cm^{-1}.

Surface-barrier detectors without thermal treatment were fabricated on the base on such silicon material before and after irradiation by various fluence of 24 GeV protons.

The concentration of carriers in not irradiated samples was measured by different methods: by Hall-effect, from depletion voltage of detectors and from C-V characteristics it was the same for these methods. In FZ silicon the concentration was $1{,}6 \cdot 10^{12}$ cm^{-3}, in silicon with oxygen it was $1{,}76 \cdot 10^{12}$cm^{-3}. There wasn't such coincidence at fluence $\geq 10^{13}$ cm^{-2}. Till fluence of protons 10^{13} cm^{-2} the detectors operate as spectrometer device. At fluence of protons $\geq 10^{13}$ detector does not operate as spectrometer device, but it can operate as counter.

Modeling Silicon Detectors with Defects

Defect kinetics modelling; a brief review and some interesting new results

Barry MacEvoy, Imperial College, London, UK

A review of the kinetics modelling carried out to date will be given. The aim of the modelling is to predict accurately the evolution of defect concentrations during irradiation for any given set of initial material impurity concentrations. The influence of these microscopic defects on electrical characteristics at the macroscopic level may then be calculated from the predicted defect concentrations on the basis of Shockley-Read-Hall (SRH) theory.

Previously published work has demonstrated that the observed changes in detector leakage current and doping concentration (N_{eff}) after irradiation with ^{60}Co photons can be described reasonably well. The defect responsible for both phenomena is identified as being the divacancy-oxygen (V_2O) complex. The changes in device behaviour after neutron irradiation are, however, described rather poorly. A possible non-SRH mechanism, based on the hypothesis of inter-centre charge transfer between clustered divacancy states in neutron-damaged devices, has been shown to resolve this discrepancy. The charge exchange process leads to a large enhancement over the SRH prediction for V_2 acceptor state occupancy and carrier generation rate.

In order to test further the predictions of the model, a comparative study of radiation hardness to ^{60}Co photons of "standard" Fz silicon ([O] ~ 5×10^{15} cm^{-3}), oxygenated Fz silicon ([O] ~ 1×10^{16} cm^{-3}) and epitaxial silicon ([O] ~ 5×10^{16} cm^{-3}) has been carried out. It is found that the changes in N_{eff} are suppressed strongly in the oxygenated detectors and even more strongly in the epitaxial detectors, where no changes are apparent even after a dose of ~200 Mrad. These results stand in contrast to studies by previous workers of hardness to fast neutrons, where identical oxygenated devices have been shown to be similar in radiation hardness to standard Fz silicon. The data set is broadly consistent with the enhanced radiation tolerance of the oxygenated and epitaxial silicon as being due to suppression of V_2O states by the increased oxygen content.

It is concluded that the improvements in radiation tolerance to neutrons achieved with epitaxial silicon are primarily due to the suppression of V_2O states. A significant fraction of the changes observed in N_{eff} after neutron irradiation are, however, thought to be due to the clustered divacancies, where a rather different approach to radiation-hardening is required. Means of confirming experimentally the contribution of V_2 to N_{eff} and of suppressing this contribution will be briefly discussed.

The role of coupled traps in irradiated Si-detectors

Karl Zankel, CERN, Switzerland

The Electric Field in Irradiated Detectors

Stephen Andrew McGarry, Lancaster University, UK

The electric field inside heavily irradiated silicon particle detectors is deduced using observations of alpha particle and MIP signals. In these detectors signals are observed for both n+ and p+ side illumination even when the detector is only partially depleted. Observations show that the electric field distribution within the detector has the expected contribution from a uniform space charge, together with a short range, local electric field in the vicinity of the p+ electrode.

The ROSE Gated Bias Diode Structures

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Universität Dortmund, Germany

The gated bias diode structures are dedicated devices to study surface effects induced by ionizing particles. It consists out of MOS-structures surrounded by p-n-diodes. To study the influence of the p-n-diode a special geometrie is choosen.

The ROSE gated bias diode structures are build out of a centered diode of 1000μm and surrounded by five MOS rings of 50μm width a 5μm gap. The inner ring is influenced by the centered diode, the outer four are in the unbiased case not influenced by the diode.

The influence is based on the fact that the depletion region below a gate ring bends the bands so that the MOS is not in equilibrium any more. The lateral expansion of the depletion region depends on the reverse voltage and can reach the outer gate ring too. This can be seen in measurements of the oxide current I_{ox} depending on the reverse voltage applied to the diode.

The band structure of a MOS-ring is influenced by the diode in the following way:

1. the reverse voltage pulls the band at the interface down
2. to reach U_{fb} a higher voltage on the gate is needed because the band bending must be compensated
3. outer rings need lower voltage for inversion than inner ones at the same reverse voltage because band bending is less than for inner ones

The measurements of the oxide current I_{ox} shows that the depletion region grows lateral with rising reverse voltage. In the case of the first gate ring the voltage for strong inversion is $U_{in}=U_{rev_{loc}} + 2*U_{fb}$. Weak inversion starts with $U_{in}=U_{rev_{loc}} + U_{fb}$ but is not significant in the measurements; the resistance is still to high.

The measurements of the C-V-characteristics of different rings whithout depleting the diode shows, that the first ring behaves different from the others. This is related to the fact that the depletion region still reaches the first ring. The inversion of this ring leads to a low resistiv contact between the MOS-inversion layer and the p-implant of the diode. So an exchange of carriers is easy and the capacitance rises with rising gate voltage instead of staying constant as usual for a MOS.

The measurements for interface state densities will be performed soon.

The effects of ionizing particels will be studied with low energie electrons of 20keV. The system for irradiating the structures is a transmission electron microscope which is working properly now. One irradiation is done under uncontrolled conditions for a preliminary test of the whole system. The flux is at maximum $4*e^{13}\frac{e}{s*cm^2}$ and a conversion factor of 50 for induced damages per electron, which corresponds to a dose of $6.7\frac{kGy}{s}$.

Numerical modeling of radiation damage of Si detectors

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[1] Universita' di Perugia, Italy
[2] I.N.F.N. Perugia, Italy
[3] I.N.F.N. and Universita' di Padova, Italy

Recent progress in the numerical simulation of solid-state detectors will be presented. A versatile modeling environment has been set up, by incorporating within a conventional 2D device simulator (i.e., a tool basically conceived for VLSI design applications) a number of radiation-related issues.

Through such an approach, i) long-term performance degradation due to radiation damage can be investigated in a fast and inexpensive fashion, and ii) physical insight of damage mechanisms can be gained, by looking at distribution of internal quantities (i.e., electric field, carrier concentration) which are difficult to estimate otherwise.

A comprehensive bulk-damage model has been considered, accounting for a generalized Shockley-Read-Hall mechanism, which includes deep-level recombination centers. Single-level and two-level approximations have been taken into account so far. Surface damage has been considered as well.

Self-consistency checks have been extensively performed, and the code sensitivity to the value of many critical parameters has been tested. Among them, values of the trap energy-level(s) and capture cross sections found have been examinated. In the framework of wider collaborations, comparisons with other CAD tools are also being carried out.

Finally, simulation results have been validated by comparison with actual device responses. To this purpose, a set of sample detectors have been irradiated with neutrons and measured. Passive characterization has been carried out, consisting in the analysis of main capacitance and resistance components; active behavior has been simulated as well: current transient responses have been predicted, allowing for estimating the device charge collection efficiency at different particle fluences.

IRRADIATED SILICON DETECTORS: a relaxation semiconductor analysis

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There is now overwhelming evidence that irradiated silicon, and irradiated and non-irradiated semi-insulating GaAs material is a relaxation semiconductor and this needs to be allowed for in measurement and analysis. This approach explains such observations asOhmic I-V, negative capacitance, capacitance peak with voltage, constant field regions and the shape of the C-V curve at medium voltages and just below full depletion. There are implications in the design and optimisation of such devices.

This will be produced as a ROSE Technical Note, but with little detailed analysis or experimental justification. A full account will be produced in two or three full papers for device journals.

We hope to have it on ROSE WWW page during March 1998.

Operation of Silicon Detectors and Damage Projections

Recent results from the PSI Si-pixel irradiation test

Beat Henrich, Paul Scherrer Inst, Switzerland

Test-devices with 8 rows of 32 n-pixels for wire-bonded analog read out have been developed at PSI to study their behaviour before and after irradiation. They were processed at CSEM Neuchâtel on 285 μm thick normal n-Silicon with 75 $\times$ 75 μm implants and 125 μm pixel pitch. The structures were exposed to fluences up to $6 \cdot 10^{14} \pi/cm^2$ with a 300 MeV/c π^+ pion beam at PSI and were operated beyond type inversion in partial depleted mode.
The method, which enabled us to make a direct measurement of the depletion depth was already presented at the last ROSE workshop and will be reviewed shortly in this talk. The partial depletion depth was monitored over one year after irradiation at V_{bias} = -300 V. In parallel a Monte-Carlo simulation program was developed to model the physical processes. The comparison between the experimental and the Monte-Carlo results will be discussed and we would like to invite the audience to give comments and contibutions that could solve some unanswered questions.
Also an outlook for future beam tests will be given.

Measured characteristics and SPICE simulation af an n+ on n type Si strip detector before and after neutron irradiation

M.M.Angarano, A.Bder, M.de Palma, G.Raso, INFN and Universita' di Bari, Italy

We have characterized single sided microstrip detectors having n+ type strips implanted over an n type substrate. They have been produced by SINTEF as a prototype for the ATLAS Semiconductor Tracker and we studied them as a back-up solution for CMS Silicon Tracker.

The detectors were irradiated by neutrons at nuclear reactor "Tapiro" in ENEA-Casaccia Laboratory (near Rome, Italy) at various fluences up to 6.9E13 n/cm^2 (1 MeV eq.). The calculated value for the hardness parameter is k=0.24. The value of the damage constant soon after irradiation is alpha=7.6E17 A/cm. We performed current, resistance and capacitance measurements before and after type inversion. We also studied the change in full depletion and breakdown voltages due to irradiation.

The irradiation had no effect on the coupling capacitances and on the bias resistors; on the other hand interstrip capacitances and interstrip resistances decreased. Most of the change in the characteristics of the frequency dependent capacitance measurements can be attributed to the decrease of the interstrip resistances and the resistance between the implantation strips and the backplain.

It was necessary to include the p+ blocking strips in our SPICE model to describe and understand the main characteristics of the frequency dependent capacitance measurements performed on an irradiated detector, which reached type inversion. In the case of an unirradiated detector a simpler model, which did not contain the p+ blocking strips, was good enough to describe the capacitance measurements. Since the frequency dependence of the capacitance value is due to the measurement method, which does not take into account the complex resistance and capacitance structure of the detector, SPICE simulation can be used to determine unmeasureable capacitance and resistance parameters.

Operation of Irradiated Silicon Detectors under Forward Bias

Alex Chilingarov, Lancaster University, UK

As was observed recently, the forward I-V characteristics of irradiated Si diodes are much less steep than they are before irradiation. This allows application of a voltage high enough to provide reasonably fast charge collection when such a detector is biased in the forward direction.

The I-V characteristics were measured for diodes irradiated by neutrons with ~1MeV energy at ISIS(RAL) up to fluences 1E+15 per cm2. An empirical parameterisation was found that allows fitting the I-V data measured at temperatures between 0 and -29C. The fluence and temperature dependences of the I-V characteristics are discussed.

The Charge Collection Efficiency (CCE) was measured for Minimum Ionising Particles (MIP) and for alpha-particles (for both sides of the detector illuminations) for forward bias operation. CCE of ~70% for MIPs was observed at bias voltages about 10 times lower than those required for such efficiency under reverse bias. The CCE for alpha-particles were low for both sides illumination, thus indicating possible low field layers adjacent to both detector electrodes.

An increase of the carrier lifetime by ~10 times was observed under forward bias which may be due to trap filling by the high current - an effect predicted in the literature.

The possible use of the forward bias mode of operation for real particle physics experiments is discussed.

ATLAS Pixel Sensors - Status and Open Questions -

Jens Wüstenfeld, Universität Dortmund, Germany

The ATLAS–experiment will be one of the largest high energy physics experiments in the near future. Its purpose for example is to study the higgs–mechanism, b–physics or supersymmetry. It will be installed in the Large Hadron Collider having a centre–of–mass energy of 14 TeV (pp–collisions). For this purpose high resolution silicon–pixel detectors have to be developed, this is the goal of the international ATLAS–Pixel collaboration.

In 1997 a first pixel–detector prototype was designed containing n–on–n pixels with dimensions of 50 x 400 μm. For interpixel isolation two different techniques have been implemented. Half of the sensors have a p–spray layer over the whole area, on the other sensors the pixels are isolated by individual p–stops. The detector wafers include several test–structures to monitor process parameters and for design studies. The design was submitted to two manufacturers, these are Seiko Instr (Japan) and CiS (Germany). The first sensor–wafers were available at the end of November for the pixel collaboration. Several tests and measurements have been performed up to now. The leakage current has been measured on unirradiated devices to check if the design works and if the sensor parameters were in the specified limits. At the PSI in Villigen a first irradiation of a choice of test–samples and sensors with 300 $\frac{MeV}{c}$ pions has been done. More detailed measurements are under way.

To make the detectors more radiation tolerant and to keep the amount of material inside the detector low it is desired to have thin sensors. The sensors in the b–physics layers (R $\approx$ 4 cm) will be 200 μm thick and for the outer layers (R $\approx$ 30 cm) the pixel material will have a thickness of 250 μm. Here the question arises if such material is available in large numbers and which manufacturers can process it. There is a problem with epitaxial material because the n–on–n pixel sensors require a double–sided process. So the substrate has to be removed before processing. Another interesting question is if low resistivity material provides more radiation hardness. For quality checks it is important to have a set of parameters which characterize the radiation hardness in view of surface and bulk damages.

Because of the restricted time–table and the CERN tendering process there will be a *point of no return*. That means, even if new results would provide better detector performance or longer lifetimes in harsh radiation areas, it is very difficult to change design or technology after that. For these reasons the ATLAS–Pixel collaboration is very interested in a close cooperation with ROSE.

Refinement of the Hamburg Group Damage Models

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Only recently there have been two major additions to the models describing the radiation damage-induced doping changes. They concern the donor removal, which appears to affect only 30% of the dopants in the original material, and the reverse annealing, which was confirmed to be a process of effectively 1st order. After briefly reviewing the experimental facts leading to these refinements, their implications for the lifetime expectancy of silicon detectors in LHC experiments will be discussed.

It is demonstrated that at best the detectors should be manufactured from the lowest resistivity material feasible, as compatible with their thickness and initial depletion voltage. Moreover, for high radiation doses, as e.g. anticipated for pixel-detectors close to the beam pipe, the warm-up period is shown to be less critical compared with the calculations based on the 2nd order reverse annealing model.

In environments with particularly high dose rates it is also necessary to take into account the freezing of the beneficial short term annealing of the doping concentration. Therefore, numerical data on the annealing time constant and the corresponding introduction rate were compiled from literature. The Arrhenius-plot of the annealing rate gives an activation energy of 1.08 eV and a frequency factor of $2.3\times10^{13}\ s^{-1}$, pointing to a single jump reconfiguration at the microscopic level. As leakage current annealing is similarly activated with 1.09 eV, it is reconfirmed that during the short term annealing period the doping concentration and the bulk generation current have a common source. The introduction rate of the annealing acceptors was found to be $1.54\times10^{-2}\ cm^{-1}$.

Finally the computation of the charge collection has been improved. So far, a constant low-field mobility had been assumed. By performing a full numerical simulation of the collection process, it is possible to take the electric field dependence of the free carrier drift velocity into account. The model now also properly deals with partial depletion.

All calculations will be illustrated by the results obtained in the analysis of the radiation tolerance of the LHC-B vertex detector. These data are currently being published as LHC-B and ROSE technical notes.

Radiation Facilities and Fluence Normalisation

Fluence Normalisation Based on the NIEL Scaling Hypothesis

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The basic problems connected with radiation damage effects to be expected for silicon detector applications in future HEP experiments result from damage of the silicon bulk mainly, produced primarily by displacements of the lattice atoms and successive processes. Hence the observed deterioration effects depend largely on the particle type and energy, being responsible for producing primary knock on atoms via individual reactions. The physical relevant quantity for the bulk damage is the Non-Ionizing Energy Loss (NIEL). There is only little doubt nowadays that this NIEL hypothesis is correct for practically all primary particles and energies. The NIEL values (as function of particle type and energy) are then taken as a very reliable possibility to normalize the different effects expected from various particles over large energy regions. The importance of the NIEL scaling hypothesis can then be summarized as serving two main purposes:

(1) Universal set of damage parameters.

intercomparison of damage results produced in test experiments with different particles and energies. This is done best with referring the individual spectral fluence distribution to an "equivalent" fluence of 1 MeV neutrons. This way we expect to obtain damage rate parameters, which are independent on particle type and energy, once we use the 1MeV equivalent fluence instead of the actual fluence value.

(2) Damage projections for future experiments.

the effects to be expected from the actual spectral distribution in a certain experimental set up (e.g. ATLAS SCT, LHC-B vertex detector or any other) can then be calculated by computing the equivalent 1MeV neutron fluence again and applying the universal parameters from (1). This (together with the annealing effects taken into account) is then the only way to gain projections of damage results to be expected for long operational durations of many years.

Taking the NIEL scaling hypothesis for granted and accepting the importance of its application for the outlined purposes, the question to be investigated is then: How reliable are the present NIEL functions for relevant particles and energy ranges. This problem was investigated here and the main results to be discussed are the following:

neutrons:

The energy spectra in LHC experiments (example ATLAS SCT) range from 100 keV to 10 GeV with a very low energy tail stretching to thermal neutrons. The best NIEL functions are believed to be the following: thermal energies up to 20 MeV: Griffin [1]; 15 - 800 MeV: Konobeyev [2]; 800 MeV - 9 GeV: Huhtinen [3]. The overlap between the different calculations is good and the whole set of data can now be used as a reliable tool. Examples of some recent

foldings and according experimental proof will be given.

pions:

The relevant pion spectrum (in e.g. ATLAS SCT) ranges from 10 MeV to 10 GeV. A fairly good study on the pion NIEL in this energy range had been performed by Huhtinen [3] including the delta resonance region. Evaluations in the delta resonance region based on pi+ cross section data have been published recently [4], but unfortunately no tables are available so far.

protons:

Also the proton energies to be expected in the ATLAS SCT are roughly ranging from 10 MeV to 10 GeV. The proton NIEL function had been studied by Summers [5] between 1 keV and 200 MeV and by Huhtinen between 15 MeV and 9 GeV. Also in this case the values in the overlapping energy range coincide.

electrons:

Reliable values for electron NIEL are reported by Summers for energies between 200 keV and 200 MeV [5]. Very little experimental results exist on NIEL normalized damage in high resistivity silicon by electrons, as most investigations have been performed by Gamma irradiations.

These specific evaluations which are now only recommended for universal use, will be discussed in detail and compared to older data sets.

A short discussion on a controversy about the relevant NIEL value for the PS proton energy of 24 GeV will be included. Taking recent measurements for comparing neutron, proton and pion induced damage parameters [6], it will be shown that the NIEL scaling is undoubtedly verified with the above reliable evaluations and should now be used by all members of the ROSE community. In order to prevent possible errors some practical points will however be discussed and illustrated by recent folding results.

The content of the talk will be soon available as a ROSE technical note and it will contain all NIEL tabulations now recommended for use.

References

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First irradiations at Karlsruhe

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New irradiation zones foreseen at the CERN-PS

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After the shutdown of the CERN-PS East Hall last September for reshuffling this experimental hall, one irradiation zone is foreseen to be operational with 24 GeV/c protons for the second half of 1998 and one irradiation zone with low energy neutrons for the beginning of 1999.

The drawings of these irradiation facilities will be presented as well as the details of the remote controlled shuttles foreseen to handle and carry the samples to be irradiated.

The results of simulations of the expected particle fluxes, the energy spectra, the radial distributions and the background will be shown. Operational details concerning the irradiation facilities will be discussed.

ROSE activities at Demokritos

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The Demokritos ROSE group has access to excellent irradiation facilities and laboratories for material characterization and evaluation of silicon detectors.

A 5MW swimming pool type reactor, at the Institute of Nuclear Technology, is capable of irradiations with fast or thermal neutrons. The irradiations with core neutrons are accomplished with a Rabbit system which places the samples close to the core for a controlled time interval. The power of the reactor can be changed so that, for example, for a 100 sec exposure one can get 1 MeV equivalent fluences between 7*10^10 and 5*10^13 n/cm^2. This range is sufficient for a complete study of defect generation on a typical silicon wafer. The thermal column of the reactor is capable of 3*10^7 n/cm^2 of 1 MeV equivalent neutrons. A detailed neutron spectrum characterization using material activation is in progress.

A pool type Co gamma source is also available, at the Institute of Material Science, capable of irradiating with 120 krad/hr. A pulsed EPR facility is available at the same institute for detailed material characterization.

A 5 MeV tandem accelerator, at the Institute of Nuclear Physics, can accelerate all ions. Proton and deuterons can reach 50 microamperes on target. The material characterization facilities include: a fully automated laser aligned RBS scattering chamber for channeling experiments, a PIXE facility etc.

Some details of the facilities will be presented. Their use for ROSE detector samples irradiations will be described.