LHCC 2002-003
LHCC P6
15 February 2002

R&D Proposal

DEVELOPMENT OF RADIATION HARD SEMICONDUCTOR DEVICES FOR VERY HIGH LUMINOSITY COLLIDERS

Dipartimento Interateneo di Fisica & INFN - Bari, Italy
D. Mauro De Palma, V. Radicci

Centro Nacional de Microelectrónica, Campus Universidad Autónoma de Barcelona, Bellaterra (Barcelona), Spain
M.Lozano, F.Campabadal, M.Ullán, C.Martínez, C.Fleta, M.Key, J.M.Rafí

NCSR DEMOKRITOS, Institute of Materials Science, Aghia Paraskevi Attikis, Greece
G.Kordas, A.Kontogeorgakos, C.Trapalis

Universitaet Dortmund, Lehrstuhl Experimentelle Physik IV, Dortmund, Germany
C.Goessling, J.Klaiber-Lodewigs, R.Klingenberg, O.Krasel, R.Wunstorf

CiS Institut für Mikrosensorik gGmbH, Erfurt, Germany
R.Röder, H. Übensee, D. Stolze

University of Exeter, United Kingdom
R.Jones, J.Coutinho, C.Fall, J.Goss, B.Hourahine, T.Eberlein, J.Adey, A.Blumenau, N.Pinho

INFN Florence – Department of Energetics, University of Florence, Italy
E.Borchi, M.Bruzzi, M.Bucciolini, S.Sciortino, D.Menichelli, A.Baldi, S.Lagomarsino, S.Miglio, S.Pini

CERN, Geneva, Switzerland
M.Glaser, C.Joram, M.Moll

Dept Physics & Astronomy, Glasgow University
M.Rahman, V.O'Shea, R.Bates, P.Roy, L.Cunningham, A.Al-Ajili, G.Pellegrini, M.Horn, L.Haddad, K.Mathieson, A.Gouldwell

University of Halle; FB Physik, Halle , Germany
V.Bondarenko, R.Krause-Rehberg

Institute for Experimental Physics, University of Hamburg, Germany
E. Fretwurst, G. Lindström, J. Stahl, D. Contarato, P. Buhmann, U. Pein, I.Pintilie

University of Hawaii
S.Parker

High Energy Division of the Department of Physical Sciences, University of Helsinki, Finland
R.Orava, K.Osterberg, T.Schulman, R.Lauhakangas, J.Sanna

Helsinki Institute of Physics, Finland
J.Härkönen, E.Tuominen , K.Lassila-Perini, S.Nummela, E.Tuovinen, J.Nysten

University of Karlsruhe, Institut fuer Experimentelle Kernphysik, Karlsruhe, Germany
W.de Boer, A. Dierlamm, E.Grigoriev, F.Hauler, L.Jungermann

Scientific Center "Institute for Nuclear Research" of the National Academy of Science of Ukraine, Kiev, Ukraine
P.Litovchenko, L.Barabash, V.Lastovetsky, A.Dolgolenko, A.P.Litovchenko, A.Karpenko, V.Khivrich, L.Polivtsev, A.Groza

Department of Physics, Lancaster University, United Kingdom
A.Chilingarov, T.J.Brodbeck, D.Campbell, G.Hughes, B.K.Jones, T.Sloan

Department of Physics, University of Liverpool, United Kingdom
P.P.Allport, G.Casse

Physics Department, King's College London, United Kingdom
G. Davies, A.Mainwood, S. Hayama, R.Harding, Tan Jin

Université catholique de Louvain, Faculté des Sciences, Unité de Physique Nucléaire – FYNU, Belgium
S.Assouak, E.Forton, G.Grégoire

Department of Solid State Physics, University of Lund, Sweden
L.Murin, M.Kleverman, L.Lindstrom

J. Stefan Institute, Particle Physics Department, Ljubljana, Slovenia
M.Zavrtanik, I.Mandic, V.Cindro, M.Mikuz

INFN and University of Milano, Department of Physics, Milano, Italy
A.Andreazza, M.Citterio, T.Lari, C.Meroni, F.Ragusa, C.Troncon

Groupe de la Physique des Particules, Université de Montreal, Canada
C.Leroy, F.Gamaz, M.-H.Genest, A.Houdayer, C.Lebel

State Scientific Center of Russian Federation,
Institute for Theoretical and Experimental Physics, Moscow, Russia
E.Grigoriev, B.Bekenov, V.Golovin, M.Kozodaev, E.Prokop’ev, A.Zaluzhnyi, V.Grafutin, A.Suvorov

Russian Research Center "Kurchatov Institute", Moscow, Russia
A. Ryazanov, V. Litvinov, P.Alexandrov, N.Belova, S.Fanchenko, S.Latushkin, V.Cvetkov, A.Brukhanov, E.Baranova

University of Oslo, Physics Department/Physical Electronics, Oslo, Norway
E.Monakhov, G.Alfieri, A.Kuznetsov, B.G.Svensson

University of Oulu, Microelectronics Instrumentation Laboratory, Finland
S.Kallijärvi, H.Nikkilä, L. Plamu, K.Remes, T.Tuuva

Dipartimento di Fisica and INFN, Sezione di Padova, Italy
D.Bisello, A.Candelori, A.Litovchenko, R.Rando

Universita` di Pisa and INFN sez. di Pisa, Italy
A.Messineo, L.Borrello, D.Sentenac, A.Starodumov

Rutgers University, Piscataway, New Jersey, USA
S.Worm, S.Schnetzer, R.Stone, L.Perera

Czech Technical University in Prague&Charles University Prague, Czech Republic
B.Sopko, D.Chren, T.Horazdovsky, Z.Kohout, M.Solar, S.Pospisil, V.Linhart, J.Uher, Z.Dolezal, I.Wilhelm, J.Broz, A.Tsvetkov, P.Kodys

Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
J.Popule, M.Tomasek, V.Vrba, P.Sicho

Ioffe Phisico-Technical Institute of Russian Academy of Sciences, St. Petersburg, Russia
E.Verbitskaya, V.Eremin, I.Ilyashenko, A.Ivanov, N.Strokan

Department of Physics, University of Surrey, Guildford, United Kingdom
P.Sellin

Experimental Particle Physics Group, Syracuse University, Syracuse, USA
Marina Artuso

Tel Aviv University, Israel
A.Ruzin, S.Marunko, T.Tilchin, J.Guskov

ITC-IRST, Microsystems Division, Povo, Trento, Italy
M.Boscardin, G.-F.Dalla Betta, P.Gregori, G.Pucker, M.Zen, N.Zorzi

I.N.F.N.-Sezione di Trieste, Italy
L.Bosisio, S.Dittongo

Brookhaven National Laboratory, Upton, NY, USA
Z. Li

Brunel University, Electronic and Computer Engineering Department, Uxbridge, United Kingdom
C.Da Via’, A.Kok, A.Karpenko, J.Hasi, M.Kuhnke, S. Watts

IFIC-Valencia, Apartado, Valencia, Spain
S. Marti i Garcia, C. Garcia, J.E. Garcia-Navarro

Paul Scherrer Institut, Laboratory for Particle Physics, Villigen, Switzerland
R.Horisberger, T.Rohe

Institute of Materials Science and Applied Research, Vilnius University, Vilnius, Lithuania
J.V.Vaitkus, E.Gaubas, K.Jarasiunas, M.Sudzius, R.Jasinskaite, V.Kazukauskas, J.Storasta, S.Sakalauskas, V.Kazlauskiene

The Institute of Electronic Materials Technology, Warszawa, Poland
Z.Luczynski, E.Nossarzewska-Orlowska, R.Kozlowski, A.Brzozowski, P.Zabierowski, B.Piatkowski, A.Hruban, W.Strupinski, A.Kowalik, L.Dobrzanski, B.Surma, A.Barcz

Abstract

The requirements at the Large Hadron Collider (LHC) at CERN have pushed the present day silicon tracking detectors to the very edge of the current technology. Future very high luminosity colliders or a possible upgrade scenario of the LHC to a luminosity of 10^{35} cm^{-2} s^{-1} will require semiconductor detectors with substantially improved properties. Considering the expected total fluences of fast hadrons above 10^{16} cm^{-2} and a possible reduced bunch-crossing interval of ≈ 10 ns, the detector must be ultra radiation hard, provide a fast and efficient charge collection and be as thin as possible.

We propose a research and development program to provide a detector technology, which is able to operate safely and efficiently in such an environment. Within this project we will optimize existing methods and evaluate new ways to engineer the silicon bulk material, the detector structure and the detector operational conditions. Furthermore, possibilities to use semiconductor materials other than silicon will be explored.

A part of the proposed work, mainly in the field of basic research and defect engineered silicon, will be performed in very close collaboration with research teams working on radiation hard tracking detectors for a future linear collider program.

Table of contents

1 Summary

The main objective of the proposed R&D program is (see Sec. 4):

To develop radiation hard semiconductor detectors that can operate beyond the limits of present devices. These devices should withstand fast hadron fluences of the order of 10^{16} cm^{-2}, as expected for example for a recently discussed luminosity upgrade of the LHC to 10^{35} cm^{-2}s^{-1}.

In order to reach the objectives and to share resources a close collaboration with other CERN and non-CERN based HEP detector related research activities on radiation damage is foreseen. The latter include for example the development of radiation hard detector material for a linear collider program. Three strategies have been identified as fundamental:

- **Material engineering**
- **Device engineering**
- **Variation of detector operational conditions**

While we expect each of the strategies to lead to a substantial improvement of the detector radiation hardness, the ultimate limit might be reached by an appropriate combination of two or more of the above mentioned strategies. Vital to the success of the research program are the following key tasks:

- **Basic studies** including the characterization of microscopic defects as well as the parameterization of macroscopic detector properties in dependence of different irradiation and annealing conditions
- **Defect modeling and device simulation,** meaning computer simulations covering the whole radiation damage process: The primary interactions of the damaging particles with the semiconductor lattice, the formation of defects, the structural and electrical properties of these defects, the impact of these defects on the macroscopic detector properties and finally simulations of the macroscopic device in the presence of defects.

To evaluate the detector performance under realistic operational conditions, a substantial part of the tests will be performed on segmented devices and detector systems.

The proposed program covers the following research fields:

- Radiation damage basic studies, defect modeling and device simulation
- Oxygenated silicon and oxygen dimered silicon
- 3D and thin devices
- Forward bias operation
- Other detector materials, like SiC

The proposed work plan covers 3 years. The collaboration will divide into dedicated working groups, which will tackle a particular aspect of the proposed research. The work will be completed by a final report and should be followed by a further research program, in which the best performing detector designs and materials are further optimized in view of experiment specific needs. This follow-up program should, in close collaboration with the experiments, focus on complete detector modules, i.e. sensors plus electronics. Engineering and integration aspects should play a key role.

2 Introduction

Future experiments at a high luminosity hadron collider will be confronted with a very harsh radiation environment and further increased requirements concerning speed and spatial resolution of the tracking detectors.

In the last decade advances in the field of sensor design and improved base materials have pushed the radiation hardness of the current silicon detector technology to impressive performance [1-3]. It should allow operation of the tracking systems of the Large Hadron Collider (LHC) experiments at nominal luminosity (10^{34}cm^{-2}s^{-1}) for about 10 years. However, the predicted fluences of fast hadrons, ranging from $3{\cdot}10^{15}$ cm^{-2} at R = 4 cm to $3{\cdot}10^{13}$ cm^{-2} at R = 75 cm for an integrated luminosity of 500 fb^{-1}, will lead to substantial radiation damage of the sensors and degradation of their performance. For the innermost silicon pixel layers a replacement of the detectors may become necessary before 500 fb^{-1} has been reached.

One option that has recently been discussed to extend the physics reach of the LHC, is a luminosity upgrade to 10^{35}cm^{-2}s^{-1}, envisaged after the year 2010 [4]. An increase of the number of proton bunches, leading to a bunch crossing interval of the order of 10 – 15 ns is assumed to be one of the required changes. Present detector technology, applied at larger radius (e.g. R > 20 cm), may be a viable but very cost extensive solution making the development of a cost optimized detector technology very eligible. However, the full physics potential can only be exploited if the current b-tagging performance is maintained. This requires to instrument also the innermost layers down to R ≈ 4 cm where one would face fast hadron fluences above 10^{16}cm^{-2} (2500 fb^{-1}).

The radiation hardness of the current silicon detector technology is unable to cope with such an environment. The necessity to separate individual interactions at a collision rate of the order of 100 MHz may also exceed the capability of available technology.

Several promising strategies and methods are under investigation to increase the radiation tolerance of semiconductor devices, both for particle sensors and electronics. To have a reliable sensor technology available for an LHC upgrade or a future high luminosity hadron collider a focused and coordinated research and development effort is mandatory. Moreover, any increase of the radiation hardness and improvement in the understanding of the radiation damage mechanisms achieved before the luminosity upgrade will be highly beneficial for the interpretation of the LHC detector parameters and a possible replacement of pixel layers.

In order to share resources and scientific results the research program will be performed in close collaboration with other R&D efforts on detector and electronics radiation hardness. Among them the research work for the linear collider program plays a major role. Groups working for this project will be also part of our collaboration since the proposed research fields of *basic research, defect engineered silicon, defect modeling and device simulation* are indispensable for the understanding of radiation damage in both high luminosity hadron and high luminosity lepton colliders.

This proposal is organized in 10 sections. In Section *"1. Summary"* a very brief overview of the proposed project is given and in Section *"2. Introduction"* the motivation is described by giving explicit examples for particle fluences to be expected in future experiments. Section *"3. Radiation Damage in Silicon Detectors"* reviews the current understanding of radiation damage on the microscopic (defects) and macroscopic (detector properties) scale and concludes in the limitations of present-day detector technologies with respect to radiation hardness. The following Section

“4. Objectives and Strategy” lists the objectives of the proposed work, outlines the strategy that was chosen to reach the objectives and explains the relation to other R&D projects. The Sections *“5. Defect Engineering”*, *“6. New Detector Structures”*, *“7. Operational Conditions”* and *“8. New Sensor Materials”* explain in detail the different approaches to achieve radiation harder detectors. They cover the approaches to modify the detector material by defect engineering (e.g. oxygen enrichment of silicon), to investigate materials other than silicon as detector material, to change the detector structure (e.g. 3D-devices) and to operate the detectors under novel conditions (e.g. forward biasing of detectors). The following Section *“9. Basic Studies, Modeling and Simulations”* describes the generic research and the simulation and modeling tools which are indispensable to reach a profound understanding of radiation damage and signal formation in detectors, which is the basis for any effort to develop new technologies. Finally Section *“10. Work Plan, Organization and Resources”* outlines the work plan, the time scale of the proposed work, the organization of the collaboration and the resources necessary to perform the proposed project.

3 Radiation Damage in Silicon Detectors

This paragraph gives a very brief overview about the present understanding of radiation damage in silicon detectors on the microscopic and macroscopic scale and outlines the resulting limits of detector operation in very intense radiation fields.

3.1 Radiation induced defects

The interaction of traversing particles with the silicon lattice leads to the displacement of lattice atoms, which are called Primary Knock on Atoms (PKA’s). The spectrum of the kinetic energy transferred to the PKA’s depends strongly on the type and energy of the impinging particle [5]. A PKA loses its kinetic energy by further displacements of lattice atoms and ionization. While displaced silicon atoms with energies higher than about 35 keV can produce dense agglomerations of displacements (clusters or disordered regions), atoms with kinetic energies below this value can displace only a few further lattice atoms. A displaced lattice atom is called an Interstitial (I) and the remaining gap in the lattice a Vacancy (V). Both vacancies and interstitials are mobile in the silicon lattice and perform numerous reactions with impurities present in the lattice or other radiation induced defects.

3.2 Radiation damage in detectors

Three main macroscopic effects are seen in high-resistivity silicon detectors following energetic hadron irradiation (see e.g. [6, 7]). These are:

- Change of the effective doping concentration with severe consequences for the operating voltage needed for total depletion (see Figure 1).
- Fluence proportional increase in the leakage current, caused by creation of generation/recombination centers (see Figure 2).
- Deterioration of charge collection efficiency due to charge carrier trapping leading to a reduction of the effective drift length both for electrons and holes.

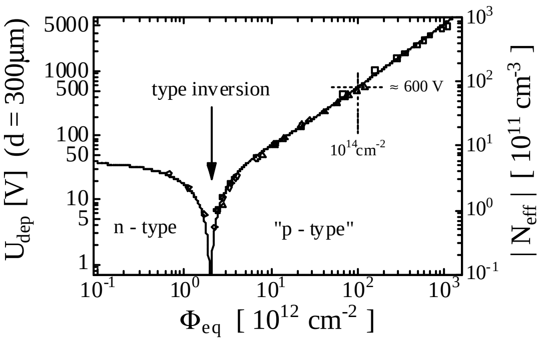

Figure 1: Example for the change of the depletion voltage with increasing particle fluence as measured immediately after neutron irradiation (no annealing) [8].

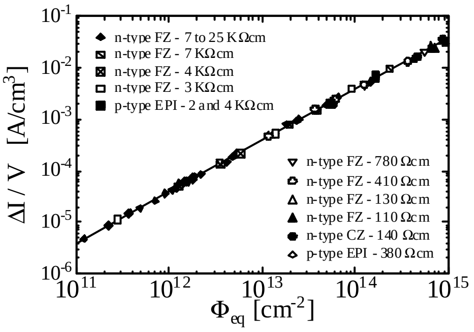

Figure 2: Increase of leakage current with fluence for different types of materials measured after an annealing of 80 min at 60 °C [9].

The first effect is the most severe for present detectors at LHC. The depletion voltage V_{dep} necessary to fully extend the electric field throughout the depth of an asymmetric junction diode (i.e. silicon detector) is related with the effective doping concentration N_{eff} of the bulk by

$$V_{dep} \approx \frac{q_0}{2\varepsilon\varepsilon_0}\left|N_{eff}\right|d^2 \qquad \text{(Eq. 1)}$$

with q_0 being the elementary charge and ε_0 the permittivity in vacuum. For a non irradiated n-type detector N_{eff} , and therefore also V_{dep}, is determined by the concentration of shallow donors (usually phosphorus) and the sign of N_{eff} is positive. Exposing the device to energetic hadron irradiation changes the depletion voltage as shown in Figure 1. With increasing fluence, V_{dep} first decreases until the sign of the effective space charge changes from positive to negative (type inversion). Then, with further increasing fluence, the depletion voltage increases and eventually will exceed the operation voltage of the device. The detector has to work below full depletion. Consequently not all charge is collected and the signal produced by a minimum ionizing particle (mip) is smaller. After irradiation, V_{dep} shows a complex annealing behavior. Here, the most severe change is the so-called reverse annealing which leads to a drastic increase of V_{dep} in the long term which can only be avoided by constantly keeping the detector below about 0 °C. This leads to strong restrictions during the maintenance of HEP detectors, which has to be performed either at reduced temperature or kept as short in time as possible. However, even when the reverse annealing can be avoided by keeping the detector cold, it is so far impossible to avoid the temperature and time independent part of the damage. The second and third effects given in the list above have direct consequences for the signal-to-noise (S/N) ratio, increase in power dissipation and deterioration in the spatial resolution for the detection of mips. However, operating the detector in moderately low temperatures of about -10 °C can largely reduce the leakage current and guarantees a sufficiently low noise and power dissipation. For the LHC experiments the trapping effects are also tolerable, however, for future very high luminosity colliders it might become the limiting factor for operation, as described in the next section.

3.3 Present limits of operation

The recent research on radiation hard silicon detectors was focused on the understanding of the detector behavior after exposure to neutron or charged hadrons fluences of up to 10^{15} cm^{-2}. At that fluence (10^{15} cm^{-2} – 1MeV neutron equivalent) several changes of the detector macroscopic parameters are observed to take place [6]. The following data correspond to an annealing state of about 14 days at room temperature (minimum of the N_{eff}-annealing curve):

- Reduction of the effective drift length for electrons ~150 μm and for holes ~50 μm at an electric field strength of 1 V/μm [10].
- Effective conduction type inversion of the material due to the presence of vacancy related radiation induced deep acceptors leading to a depletion starting from the n-contact.
- Fluence proportional increase of leakage current per unit volume due to the presence of radiation induced generation/recombination centers ($I/V \approx 30$ mA/cm^3 at 20 °C).
- Negative space charge increases to ~$1.5{\cdot}10^{13}$ cm^{-3} for non-oxygenated silicon, requiring ~1000 V for 300 μm full depletion.
- Presence of reverse annealing, or increase of the negative space charge after long term annealing at room temperature.
- Deterioration of the charge collection efficiency due to a combination of trapping and incomplete depletion, both for pixel [11] and strip detectors.

4 Objectives and Strategy

4.1 Objectives

The main objective of the R&D program is:

To develop radiation hard semiconductor detectors that can operate beyond the limits of present devices. These devices should withstand fast hadron fluences of the order of 10^{16} cm^{-2}, as expected for example for a recently discussed luminosity upgrade of the LHC to 10^{35} $cm^{-2}s^{-1}$.

Further objectives are:

To develop new low-cost radiation hard detector technologies to instrument the intermediate tracker region (R = 20 to 50 cm). Although today’s pixel technology is in principle able to operate in this radiation environment, the corresponding sensor area to be covered requires very cost effective technologies.

To make recommendations to experiments on the optimum material, device structure and operational conditions for detectors and on quality control procedures required to ensure optimal radiation tolerance. These recommendations should be supported by tests performed on a generic demonstrator detector system tested under realistic operational conditions.

To achieve a deeper understanding of the radiation damage process in silicon and other detector relevant semiconductors with the aim to reach the above-mentioned goals and to support and collaborate with other HEP detector related research activities on radiation damage. The later include for example the development of radiation hard detector material for a linear collider program.

4.2 Strategy

Based on the achievements of past and present CERN R&D projects [12-17] and recent discoveries in radiation hard semiconductor devices, three fundamental strategies have been identified in order to achieve radiation harder tracking detectors. These are:

- **Material engineering**
  Material engineering stands for the deliberate modification of the detector bulk material. One approach is the defect engineering of silicon (Section 5), which for example includes the enrichment of the silicon base material with oxygen, oxygen dimers or other impurities. Another approach is the use of other semiconductor materials than silicon (Section 8) such as e.g. silicon carbide.
- **Device engineering**
  This strategy stands for the improvement of present planar detector structures by e.g. the modification of the electrode configuration or the thinning of the bulk material and the development of new detector geometries such as 3D detectors (Section 6).
- **Variation of detector operational conditions**
  Investigations of the optimum detector operational conditions include for example the operation of silicon detectors at low temperatures or under forward bias (Section 7).

While we expect each of the three strategies to lead to a substantial improvement of the detector radiation hardness, the ultimate limit might be reached by an appropriate combination of two or more of the above-mentioned strategies. Absolutely vital to the success of our research program is a profound understanding of the physics underlying the radiation-induced degradation of detector properties and the charge collection capabilities of different detector types. This needs:

- **Basic studies**
  With basic studies we mean the characterization of microscopic defects as well as the parameterization of macroscopic detector properties under different irradiation and annealing conditions.
- **Defect modeling and device simulation**
  These are computer simulations covering the whole process of radiation damage: The primary interactions of the damaging particles with the semiconductor lattice, the formation of defects, the structural and electrical properties of these defects, the impact of these defects on the macroscopic detector properties and finally simulations of the macroscopic device in the presence of defects.

To evaluate the detector performance under realistic operational conditions, a substantial part of the tests will be performed on segmented devices:

- **Test of segmented devices and detector systems**
  We plan to characterize radiation damage effects on segmented test structures (e.g. mini-strips or pixels). At the same time we will perform tests on simple detector systems that will allow for an evaluation in terms of speed, signal/noise, spatial resolution, efficiency and sensor power dissipation.

A work plan for the 3 years of the proposed project is given in Sec.10. We plan to explore all materials and technologies described above to the limits required by a high luminosity collider, namely very high gamma and charged hadrons fluences. This process will include both simple structures, crucial for material studies, and segmented devices, like pixels and microstrips, associated with the state of the art available readout electronics. The research process will be concluded with a recommendation for the optimal detector materials, detector designs and detector operational conditions. Furthermore, a follow-up research program for the most promising and feasible technologies focused on the further improvement of these technologies and their transfer into the experiments will be proposed.

4.3 Collaborations with other R&D projects

In order to share resources and scientific results, the research program will be performed in close collaboration with other R&D efforts on detector and electronics radiation hardness issues:

- **Research for the Linear Collider Program**
  The radiation damage in the linear collider detectors will be dominated by fast lepton damage which produces on the microscopic level mainly point defects while for the detectors in the hadron collider experiments the damage is composed of point defects and clustered defects. An investigation of electron damage therefore offers the possibility to separately investigate point defects. It is obvious that the understanding of point-like defects is the basis for the understanding of the much more complex hadron damage.
  Although the hadronic component of the radiation damage is very small in linear colliders it is not negligible and might be the most severe problem in terms of radiation hardness. Therefore a defect engineered material, being more radiation tolerant against hadron damage, is of high interest for the linear collider. A good example for a common interest is for example the oxygen enriched silicon which is not only more resistant against charged hadron irradiation but offers also a much higher radiation hardness against gamma and electron irradiation [6, 18-20].

  Although the foreseen detector requirements and the expected radiation fields in a linear collider experiment differ strongly from that of a hadron collider experiment, there are common interests in the basic research (Sec.9) and the defect engineering of silicon (Sec.5).

- **Other R&D collaborations at CERN**
  Other important topics already covered at CERN by other R&D projects are the development of cryogenic silicon detectors (RD39), diamond detectors (RD42) and radiation tolerant electronics (RD49). An exchange of expertise is foreseen through common tests and workshops.

5 Defect Engineering

The term “defect engineering” stands for the deliberate incorporation of impurities or defects into the silicon bulk material before, during or after the processing of the detector. The aim is to suppress the formation of microscopic defects with a detrimental effect on the macroscopic detector parameters during or after irradiation. In this sense defect engineering is coping with the radiation damage problem at its root.

5.1 Oxygen enriched silicon

The CERN RD48 (ROSE) Collaboration introduced oxygen-enriched silicon as DOFZ (Diffusion Oxygenated Float Zone Silicon) to the HEP community [16]. The DOFZ technique was first employed by Zheng Li et al. on high resistivity FZ silicon [21] and consists of diffusion of oxygen (e.g. for 24 hours at 1150°C) into the silicon bulk from an oxide layer grown via a standard oxidation step. Figure 3 shows examples of oxygen depth profiles in different DOFZ samples as measured with the Secondary Ion Emission Spectroscopy (SIMS) method [7].

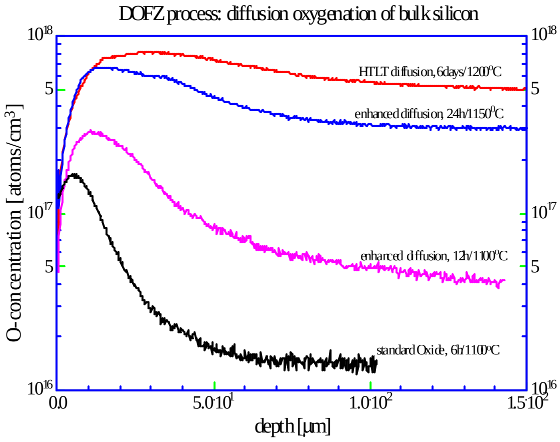

Figure 3: Oxygen depth profile as measured by SIMS after different oxygen diffusion processes [7] (HTLT = High Temperature Long Time; enhanced diffusion = higher temperature and/or diffusion time than in a standard oxidation).

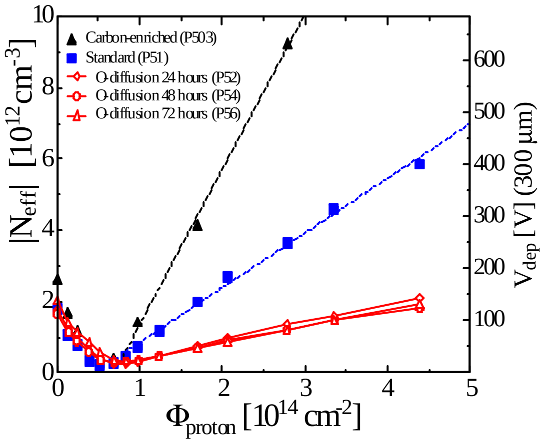

Figure 4: Influence of Carbon and Oxygen on the depletion voltage V_{dep} [7]. The samples were irradiated in a so-called “CERN-scenario”[1].

RD48 demonstrated in 1998 that the oxygenated material is highly superior in radiation tolerance with respect to charged hadrons [22]. The main properties of oxygen-enriched silicon are described in [6, 7, 18] and are summarized in the following:

The increase of negative space charge (i.e. the increase of depletion voltage after type inversion) is reduced by about a factor of 3 for high energy charged hadrons. This is shown in Figure 4 for 23 GeV protons and was also observed for 192 MeV pions. Furthermore, for low energy protons in the energy

---

[1] “CERN-scenario”: The samples were irradiated in several steps and the fluence indicated in the graph is the cumulated fluence. After each irradiation step the samples were heated for 4 min at 80°C and then the depletion voltage was measured. Afterwards the same sample was irradiated again.

range of 16-27 MeV a reduction of about 2 was observed [23]. However, the two improvement factors have been determined with different sets of “standard materials”[2]. This makes it difficult to compare the results since a wide variation of the increase of the negative space charge with the 23 GeV proton fluence has been observed for “standard materials” while only oxygen-enriched diodes showed reproducible results [24]. Therefore, further irradiations with the same “standard material” and a wide range of proton energies are necessary to characterize the oxygen-effect in more detail. After neutron irradiation no such improvement for this damage component was observed.

After irradiation with 23 GeV protons and 192 MeV pions a saturation of the reverse annealing amplitude (i.e. the increase of the depletion voltage during the long term annealing) was observed at high fluences for the oxygenated silicon, amounting to a reduction factor of up to 3 for DOFZ diodes. The time constant for this process is at least a factor of 2 larger. Thus both improvements provide a substantial safety margin for the effects to be expected during the warm up maintenance periods. Furthermore, the leakage current is not influenced by the oxygen content [25] and the DOFZ process does not influence the surface and interface properties [26].

The implementation of the DOFZ technique in the detector processes of manufacturing companies was initiated by RD48 and led to considerable experience of many detector producers. Oxygenated strip and pixel detectors have meanwhile been extensively tested [27, 28, 29]. The ATLAS-Pixel collaboration is using DOFZ silicon and the CMS-Pixel collaboration will most likely use this technology. However, there are still many open questions regarding the optimization of the technology and the understanding of the oxygen effect:

- **Why does oxygen improve the radiation tolerance?**
  There are many ideas about the microscopic mechanisms underlying the oxygen-effect. However, so far the responsible microscopic defects produced in hadron irradiation have not been clearly identified and further defect characterization studies are necessary (see Section 9.1.1). It is however very promising that for gamma irradiation a direct correlation between a microscopic oxygen-related defect and the macroscopic changes of the detector properties was found in a recent experiment [30]. In fact 70% of the current increase and 90% of the change in the doping concentration in standard detectors could be attributed to the formation of a deep defect at E_c-E_t = 0.543 eV which is likely to be identified as the V_2O center. Fig. 5 shows DLTS[3] spectra clearly displaying the dose dependence of the defect concentration. In DOFZ silicon the concentration was below detection limit for the same dose-values.

  One further very promising approach to understand the role of oxygen for the radiation hardness of silicon detectors, that was so far not tried, is the production and irradiation of a ^{17}O-doped DOFZ silicon sample. This would for example allow studying the structure of radiation-induced defects in the environment of the ^{17}O atoms and defects containing a ^{17}O atom in great detail with pulsed EPR techniques[4].

---

[2] “Standard material”: Silicon wafers as delivered from the producer without additional oxidation step (no oxygen enrichment).

[3] A short description of the Deep Level Transient Spectroscopy (DLTS)–technique is given in Sec.9.1.1.

[4] Electron Paramagnetic Resonance (EPR) is explained in Section 9.1.1

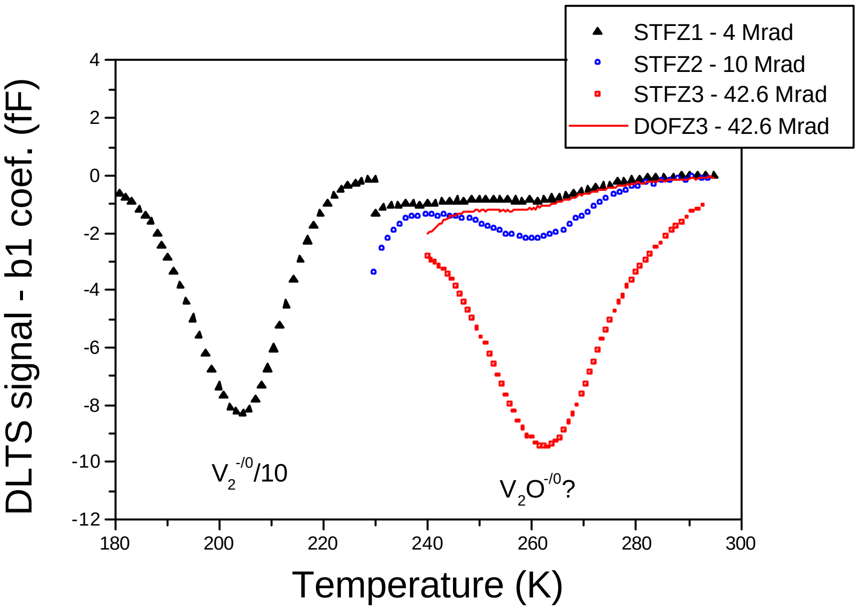

Figure 5: Majority carriers (electrons) DLTS spectra (DLTS time window: T_w=200 ms) recorded on standard (STFZ) and oxygenated (DOFZ) silicon detectors exposed to high doses of ^{60}Co – gamma irradiation. The peak at about 260 K was tentatively assigned to be due to the V_2O defect (divacancy-oxygen) while the peak at about 200 K is due to the well-known divacancy (V_2). The V_2 defect could only be measured for the lowest dose and is scaled by a factor 0.1 in the figure. For the larger doses the V_2 concentration is higher than the free carrier concentration making a DLTS measurement below about 230 K impossible.

- **Quantitative correlation between oxygen content and radiation hardness?**
  Although the beneficial effect of O-enrichment on the radiation tolerance has been conclusively established in many experiments with detectors originating from many different producers, no clear quantitative correlation between the oxygen content and the improvement of the radiation hardness could be established. It seems that there is an impact of the individual processes of the different manufacturers, which has so far not been understood. For the use of oxygenated silicon in future and present applications the clarification of these questions is regarded as very important.
- **Reliable characterization of Oxygen and Carbon profiles and simulation of O-diffusion**
  For the measurement of Oxygen and Carbon profiles in high-resistivity-detector-grade silicon the SIMS (Secondary Ion Emission Spectroscopy) method has to be operated close to its detection limit. An absolute calibration is therefore absolutely necessary [31, 32]. Simulations of the oxygen diffusion profiles are necessary to understand the shape of the oxygen profile measured by SIMS [33].
- **Optimization of DOFZ process**
  So far the DOFZ process has been studied in a range between 16h/1150°C and 8d/1200°C. SIMS measurements have shown that for the low in-diffusion process one gets a quite inhomogeneous O-distribution while in the latter case the depth profile is almost constant. The optimal process with respect to radiation hardness and cost effectiveness has to be found.
- **More detailed characterization of oxygenated detectors**
  The oxygenation process significantly suppresses the reverse annealing. This needs to be understood, as more improvement may be possible.
- **High resistivity Czochralski Silicon (CZ)**
  New developments in the silicon manufacturing technology make high resistivity CZ possible. This material might be cheaper than DOFZ and exhibit the same or even better radiation tolerance.

5.2 Oxygen dimer in silicon

Recent work [34] has shown that it is possible to convert oxygen interstitials O_i to oxygen interstitial dimers O_{2i} in silicon. There are two main reasons why this is interesting for further developments of radiation tolerant detectors.

First, O_{2i} may be more effective than O_i at improving the radiation tolerance. For instance, V_2O_2 is thought to be electrically neutral unlike V_2O, which is an acceptor close to mid-gap. Secondly, O_{2i} is thought to diffuse more rapidly through silicon than O_i. Activation energies for migration of O_i and O_{2i} are 2.54 eV and 1.8 eV respectively. Thus a possible way to oxygenate silicon wafers in a short time is to introduce O_i into the surface of the wafer by a short high temperature diffusion, convert this O_i to O_{2i}, and then thermally diffuse the O_{2i} into the bulk of the wafer at a much reduced temperature. This would result in a shorter diffusion time and lower furnace temperature when preparing the oxygenated silicon material. Secondly, VO can be both an electron and hole trap, depending on its charge state, while VO_2 is electrically neutral. In particular, VO is thought to be the main charge trap in cryogenic temperature forward bias operation, limiting the maximum charge collection efficiency at high fluences for this mode of operation.

Oxygen dimer silicon diodes have been produced with $10^{15}/cm^3$ carbon, low ($10^{15}/cm^3$) and high ($10^{17}/cm^3$) oxygen concentration, n-type, 4 kΩ-cm resistivity silicon diodes. For the dimerisation they were irradiated at 350°C using a Cobalt-60 gamma source. Previously, a similar process has been tried using 2 MeV electrons [34]. The gamma source has the advantage of uniformly producing interstitial-vacancy pairs throughout the silicon. Moreover, divacancies V_2 are produced a factor 50 less than single vacancies V [35].

The quasi-chemical reactions that are thought to lead to Oxygen dimer formation are [36]:

$V + O \Rightarrow VO,$
$VO + O \Rightarrow VO_2,$
$I + VO_2 \Rightarrow O_2.$

The success of the process was proven in both samples (low and high oxygen concentration) by the absence of the DLTS VO (Vacancy Oxygen) peak ,E(90)[5], after proton irradiation, as shown in Figure 6 [38]. The E(170) peak, which has been correlated with VOH (Vacancy Oxygen Hydrogen), is present after the dimerisation process with a concentration of $5\cdot 10^{11}$ cm^{-3}. This concentration does not change after proton irradiation and it is too small to have any influence on the final concentration of radiation-induced defects.

Reverse annealed samples measured at –50 °C show a lower space charge build-up, correlated with the intensity of the DLTS peak E(225) associated with the di-vacancy V_2 cluster, for the low oxygen dimered sample [37].

---

[5] The abbreviation E(90) indicates that the corresponding defect is emitting an electron (E) and leads to a peak in the DLTS spectrum with a maximum at 90 K.

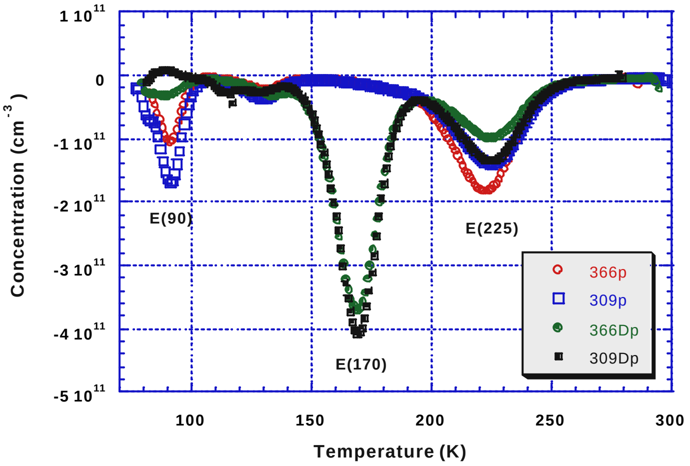

Figure 6: DLTS spectra of high (309) and low (366) oxygen content silicon diodes. D indicates that the sample underwent dimerization process. In both 366D and 309D sample the VO (Vacancy-Oxygen) E(90) peak has disappeared [38].

The potential of this material for radiation hardness applications has been discovered very recently. Systematic study is needed to understand the role of oxygen dimer in defect formation and device performance. Detailed measurements are required to understand:

- Optimization of dose rate and exposure time during material processing
- Defect formation (Infra Red Absorption, DLTS, Electron Paramagnetic Resonance (EPR), positron lifetime)
- Space Charge and Reverse Annealing
- Charge Collection Efficiency
- Charge carrier lifetime
- Low temperature and forward bias behavior

6 New Detector Structures

Signals on any of one of the segmented electrodes of a semiconductor tracking detector are developed when the electric field lines from charge carriers that terminate on that electrode change due to the motion of the charge carriers. The signal formation is described by the Ramo-Shockley theorem [39-42] via the weighting potential $V_w(\mathbf{r})$, which is the solution of the Laplace's Equations $\Delta V_w=0$ for the weighting potential at the signal electrode equal to 1 and at all other electrodes $V_w=0$. For a highly segmented detector the weighting potential has a nearly exponential increase of its value towards the collecting electrode. This results in the carriers moving towards the collecting electrode dominating the signal at it.

After irradiation the drift of the carriers is limited by the charge trapping at the radiation induced defects. The effective drift length is $L_{eff} = \tau_t \cdot v_{drift}$, where τ_t is the carrier trapping time and V_{drift} is its drift velocity. This parameter has been measured and simulated to be ~150 µm for electrons and ~50 µm for holes [10, 37] in an electric field of 1 V/µm after a fluence of $1{\cdot}10^{15}$ particles/cm^2. Taking into account the charge trapping, that part of the signal at an electrode due to charge moving toward the electrode and arising from a charge pair +q-q released at the distance x from it can be approximately expressed as:

$$Q_{\text{signal}} \sim q\,\left(1 - V_w(x)\right)\exp\!\left(-{}^{x}\!\big/_{L_{\text{eff}}}\right) \qquad \text{Eq. 2}$$

where $V_w(x)$ is the weighting potential in the point x and L_{eff} is the effective drift length for the carriers moving towards the electrode. It follows that a segmented detector after $1{\cdot}10^{15}$ particles/cm^2 should (see also [29]):

- Collect electrons and not holes;
- Have an optimized electrode configuration and detector thickness.

6.1 3D detectors

The radiation hardness of 3D detectors is geometric in nature and the corresponding improvement factors will generally multiply with those coming from material improvements. The main characteristic of the 3D detector concept is shown in Figure 7 and consists in fabricating p and n electrodes through the bulk in form of narrow columns instead of being deposited parallel to the detector surface. While in a conventional silicon sensor the depletion and charge collection across the full wafer thickness (usually 250 - 300 µm) requires very high voltages and becomes incomplete after high radiation levels, the main advantage of this approach is the short distance between collecting electrodes. This allows at the same time very fast collection times, very low full depletion bias voltage (~10 V), low noise and the full charge collection with about 25 000 e/h provided by the 300 µm detector active thickness.

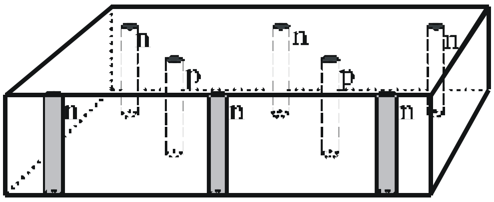

Figure 7: Schematic, three-dimensional view of part of a sensor with 3D electrodes penetrating through the substrate. The front border of the figure is drawn through the center of three electrodes.

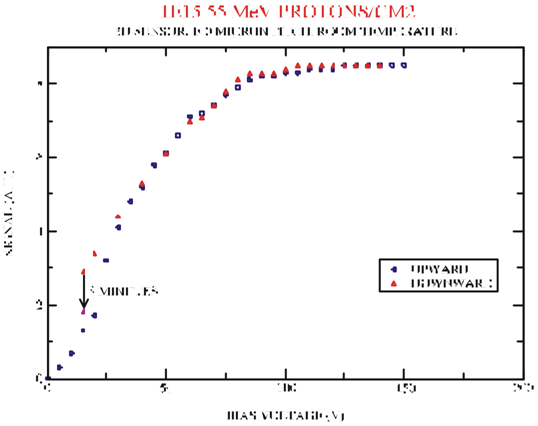

Figure 8: 3D detectors signal after irradiation with a fluence of $1{\cdot}10^{15}$ 55 MeV protons/cm^2. The hardness factor corresponds to $1.7{\cdot}10^{15}$ 1 MeV equivalent neutrons/cm^2. [43].

After irradiation with protons up to $1{\cdot}10^{15}$ 55 MeV protons/cm^2, see [43], a sensor with 100µm n-n separation is fully depleted at 105 V (see Figure 8) and has a plateau up to 150 V. Leakage currents for unirradiated sensors range from about 0.25 to 1.25 nA/mm^3 of depleted silicon. The increase of leakage current with irradiation is similar to those of similar planar detectors.

6.2 Thin detectors

Similar considerations as for the 3D detectors can be applied to thin detectors. The basic advantage of thin devices relates to the optimized use of the effective drift length of the carriers while having a low full depletion voltage. Moreover, this leads to a significant reduction of the material budget, which would improve the overall particle momentum resolution.

The planar 300 µm silicon detectors have been so far a reasonable compromise between signal/noise, silicon availability and ease of mechanical handling. Thin, low mass semiconductor trackers would have many advantages in future experiments, as in some respects has been shown already by the use of CCDs at SLAC [44]: better tracking precision and momentum resolution, more precise timing (not compatible with CCD/monolithic devices), lower operating voltage, lower leakage currents and improved radiation hardness. As discussed above, even after a high dose, both the electrons and the holes still can be collected over 50 µm so that it may be feasible to retain a p^+n segmented diode structure for a thin detector. However, the m.i.p. signal from such a thin, 50 µm, silicon sensor layer is only ~3500 e-h pairs, with a relatively broad Landau distribution towards higher values. Only with the small pixel concept readout electronics can one have sufficiently low noise at ns timing.
The problems related to this approach are purely technical since both, processing on thin devices is difficult, as well as thinning after processing. Industry has expressed high interest in thin silicon devices mainly for credit cards and smart cards. Work should be done, closely with industry, to process low cost, reliable samples to be tested with or without readout electronics. A precise cost estimate is very difficult at this stage, without R&D.
The use of thin detectors would also offer the possibility to use low resistivity silicon. A detector of a thickness of 50 µm and a resistivity of 50 Ωcm would have for example a depletion voltage of roughly 200 V. However, assuming the present knowledge to be valid, this material would only undergo type inversion at a fluence in the order of $1{\cdot}10^{15}$ particles/cm^2.

6.3 Cost-effective solutions

In the experiments presently under construction the regions with fluences between $5{\cdot}10^{14}$ and $1{\cdot}10^{15}$ cm^{-2} (1 MeV-neutron-equivalent) are instrumented with pixel detectors using n on n sensor technology. They are capable to withstand these particle fluences because the n on n sensors can be operated strongly underdepleted after irradiation induced type inversion, the pixel electronics accepts the heavily reduced signals as the small pixel capacitances contributes only a small noise. The n on n pixel technology is however too expensive to instrument very large areas as they may be required for the intermediate tracker region (R = 20 - 50 cm) at future high luminosity hadron colliders.

The most cost driving issues are:

- the need to cover the whole detector area with readout electronics and
- the double sided sensor technology.

The total coverage can be avoided if the sensor cell size is larger than the chip area needed for one readout channel. The signals will then have to be routed from the sensor cell to the chip input using e.g. the MCM-D (Multi Chip Module-Deposited) technology [45]. In order to reduce costs further this technology might be used to integrate the complete HDI (High Density Interconnect). The savings are not only the chips themselves but also the reduced infrastructure, which has to be provided (cooling, optical links, power supplies etc.)

Moving from double sided processed to a single sided sensor technology has the potential to reduce the sensors costs by more than a factor of two. However the problem of the sensor edges on high potential has to be solved. Possible candidates are thin sensors if producible cost-effective in large quantities. An alternative might be n on p-substrate sensors, which can be produced in a standard single sided process. However its design has to be optimized for very high operation voltages after irradiation.

7 Operational Conditions

The Charge Collection Efficiency (CCE) recovery of heavily irradiated planar standard silicon detector operated at a temperature around 130 K, known as the “Lazarus Effect”, was one of the subjects studied by the RD39 collaboration [14]. The same collaboration is also studying effective ways to overcome space charge polarization effects at low temperatures. This can be done by forward bias operation [46], as previously demonstrated also by the Lancaster group close to room temperature [47], or by current injection using light [14]. Temperature can also be used to control the space charge. The operation of highly irradiated detectors under forward bias or by using other techniques to induce free charge into the detector bulk is not only a promising operational condition for low temperatures around 130 K but can also improve the detector performance at higher temperatures [47]. Therefore, it is foreseen to perform tests under such conditions on any of the new materials and devices whenever it is promising an improvement of the radiation tolerance. In cases where cryogenic temperatures are approached we will strive for a close collaboration with RD39 in order to profit from their expertise and bundle resources.

8 New Sensor Materials

The radiation hardness properties of diamond detectors for the LHC have been the subject of study of the RD42 collaboration [15]. Other materials, however, have been recently recognized as potentially radiation hard. Some of them are listed hereafter with their basic radiation hard properties.

8.1 Silicon Carbide

Semi-insulating 4H-SiC has the intrinsic possibility of being a radiation hard particle detector. 4H-SiC has a large band gap (3.3 eV), e-h pair generation per 100 um per MIP (5100 e) and a low carrier density, which implies a low leakage current and high initial resistivity, as high as 10^{11} Ωcm. at room temperature. The present wafer dimension is 30 mm, but the detector-processing yield is still limited due to high as-grown defect concentration present in the material. After irradiation with ~$4{\cdot}10^{14}$ cm^{-2} 8 GeV protons the measured charge in a 310 μm thick detector was ~2000 e, with 500V bias voltage. Polarization was also observed with a time constant of ~14 min and a final charge of ~800 e [48].

8.2 Amorphous Silicon

Amorphous silicon has been extensively used for solar cells applications, flat panels displays and optical scanners. Its use is possible due to the hydrogenation process (a-Si:H) which allows the passivation of the intrinsic dangling bonds present in the material, due to missing atoms in the Si amorphous structure. The presence of the dangling bonds would prevent the use of such material as radiation detectors since they act as very effective recombination centers for electrons. At present Metal Insulator Semiconductor (MIS) and PIN structures have been fabricated up to thickness of tens of microns using Radio-frequency Plasma Enhanced Chemical Vapor deposition (PECVD). The Charge Collection Efficiency (CCE) for 5.5 MeV alpha particles was measured to be 1% [49].

8.3 GaN- and AlGaAs-based materials

Many of the compound semiconductors have been extensively studied for their optical properties; alloys of GaN for example have been successfully employed in the fabrication of blue lasers. Pure growth processes such as molecular beam epitaxy (MBE) and metal organic vapour deposition (MOCVD) permit the growth of relatively pure epitaxial layers, although not always on lattice matched substrates. Technologies for manufacture of bulk materials are continuously under improvement and may permit future detector grade media. Particularly attractive are the very large bandgaps that are possible (eg up to ~6 eV for AlGaN). Other combinations of alloys (eg AlGaAs) offer the further possibility of electron gain due to avalanche processes, giving an interesting prospect for enhanced signal collection.

9 Basic Studies, Modeling and Simulations

The radiation-induced changes of the macroscopic silicon detector properties – leakage current, depletion voltage, charge collection efficiency – are caused by radiation induced electrically active microscopic defects (see also Section 3). Therefore, a comprehensive understanding of the radiation induced detector degradation can only be achieved by studying the microscopic defects, their reaction and annealing kinetics and especially their relation to the macroscopic damage parameters. Furthermore, modeling of defect formation and device simulations are needed to understand the complicated defect formation mechanisms and the operation of irradiated structured devices.

These kinds of studies are of fundamental interest for all semiconductor-based devices (sensors and electronics) operating in a radiation environment. In order to exploit the common interest of several groups working in this field a close collaboration with the RD39 [14], RD42 [15] and RD49 [17] collaborations at CERN and the LCFI (Linear Collider Flavour Identification) [50] collaboration working for the TESLA project is foreseen. We envisage joint research activities and research status exchanges in the respective collaboration meetings.

9.1 Basic Studies

9.1.1 Investigations on microscopic defects

In the last years many measurements on radiation induced microscopic defects in high resistivity FZ silicon have been performed. However, the exact nature of the defects which are responsible for the macroscopic radiation damage are still not fully known. We propose therefore the following work:

- **Defect characterization with various different techniques**

Besides the techniques of Deep Level Transient Spectroscopy (DLTS), Thermally Stimulated Current (TSC) and Transient Charge Technique (TCT), which have been extensively used in the past years for defect characterization in detector silicon, also techniques like Photo Luminescence (PL), Electron Paramagnetic Resonance (EPR) and Fourier Transform Infrared absorption (FTIR) need to be used, especially since the last two give structural information about the defects. Furthermore lattice defects and their annealing are envisaged to be investigated with Tunneling, Atomic Force and Atom-probe Field Ion Microscopes [51]. Techniques to investigate on the change of the free carrier lifetime during irradiation and annealing will be applied. In the following only two techniques will be described for measuring the electrical (DLTS) and structural (EPR) properties of defects in semiconductors.

- **Deep Level Transient Spectroscopy (DLTS)**

  By monitoring capacitance transients produced by pulsing the voltage applied to the semiconductor junction at different temperatures, a spectrum is generated which exhibits a peak for each deep level (see e.g. Figure 6). The height of the peak is proportional to trap density and its sign allows one to distinguish between electron and hole traps. The position of the peak on the temperature axis leads to the determination of the fundamental defect parameters: defect concentration (N_t), capture cross section for holes ($\sigma_{h,t}$) and electrons ($\sigma_{e,t}$) and energy level (E_t) within the band gap. These parameters are governing the thermal emission and capture of charge carriers and allow e.g. for the calculation of the defect induced trapping time.

- **Electron Paramagnetic Resonance (EPR)**

  EPR is a branch of spectroscopy in which electromagnetic radiation of microwave frequency is absorbed by atoms in molecules or solids, possessing electrons with unpaired spins. EPR spectroscopy contributed substantially to the understanding of the atomic structure, formation and disappearance of defects and interaction of paramagnetic centers. Recent developments in instrumentation and theory have made possible powerful extensions of the basic EPR spectroscopy, greatly enhancing its resolution and sensitivity to atomic arrangements, bond angles, structure of interfaces and time-dependent phenomena such as motion of ions in solids [52, 53]. These advanced methods offer the possibility for the precise determination of the structure of paramagnetic states, where conventional EPR spectroscopy suffers from limited energy and time resolution. We therefore propose the employment of recently developed pulse EPR and pulse ENDOR (Electron-Nuclear Double Resonance) techniques in the characterization of radiation- induced damage in silicon and other semiconductors. Two pulse EPR spectra will be recorded and evaluated. The ESEEM (Electron Spin Echo Envelope Modulation) spectra will be modulated in the presence of the neighboring nuclear spins. The analysis of the amplitude of modulation will give the kind, number and distance of the nuclei surrounding the unpaired state. These and further techniques will be used in order to evaluate for the first time in a systematic study the environment of the defects in irradiated semiconductors for distances up to 40 Å.

- **Irradiation at different temperatures – online measurements at low temperatures**
  Both vacancies and interstitials migrate rapidly at room temperature. It is therefore impossible to directly investigate the formation of most of the defects since they are formed too quickly. Only by performing irradiation in the cold can the migration process be stopped ("frozen") and a deeper insight into the defect formation process can be taken. Such measurements have either to be performed on the beam line (irradiation facility) or the samples have to be transported cold to the measurement setup.

9.1.2 Investigations on irradiated detectors

Extensive experiments on the radiation induced changes of detector properties and their dependence on particle fluence, particle type and energy, temperature and annealing time are indispensable. They not only open the door for a profound understanding of the relationship between microscopic defects and detector properties but also are absolutely necessary to predict the radiation damage effects in the tracker experimental environment. The following topics need to be investigated in more detail:

- **CCE (Charge Collection Efficiency)**
  Up to now most systematic investigations on the radiation-induced changes of the effective doping concentration have been based on depletion voltage measurements as extracted from Capacitance-Voltage (CV) measurements. However, systematic charge collection measurements, either performed with a laser (difficult for an absolute calibration) or with mips, have to be performed in systematic investigations to also parameterize the trapping behavior in more detail.
- **Comparison between pixels, full-size or mini strip detectors and simple test structures**
  Such measurements are closely related to investigations on the dependence of CCE and electric field distribution on the device structure.
- **Irradiation under bias at operating temperatures (e.g. -10°C)**
  So far, most of the irradiations have been performed without applied bias and in a room temperature ambient. It has been shown that the irradiation under bias has an influence on the annealing behavior of the depletion voltage [54]. Since detectors are operated under bias and at temperatures below ambient temperature, these effects have to be investigated in more detail.
- **Establishment of comparable measurement procedures**
  There exists no agreed common measurement procedure for irradiated detectors. Detector treatments after irradiation (annealing procedure) differ strongly from community to community and make inter-comparison very difficult.
- **Systematic investigations on the particle and energy dependence (NIEL)**
  It has clearly been demonstrated by the ROSE collaboration that the so-called "NIEL-Hypothesis" is not valid for all damage parameters. This implies that irradiation tests with a much wider range of particle energies must be performed.
- **Lorentz angle measurements in silicon detectors**
  Future experiments are using silicon detectors in very high magnetic fields, e.g. 4 T in the case of CMS [3]. It is important to understand the influence of the magnetic field on the charge drift in highly irradiated detectors under different operational conditions [11, 55].

- **Combined investigation with state of the art radiation hard electronics**
  Radiation hard electronics is fundamental for the proper functioning of a silicon tracker. The RD49 collaboration has already developed effective design strategies for the existing LHC experiments [17] and is planning new improvements for the high luminosity scenario. Close contacts are foreseen with the RD49 groups and combined tests are planned to evaluate small-scale radiation-hard modules.

9.2 Modeling and Simulation

9.2.1 Modeling of defect formation

Modeling of defect formation is indispensable for the understanding of the radiation damage process and the development of new defect-engineered materials [56]. Recently M.Huhtinen [5, 57] presented a very comprehensive simulation covering the full radiation damage process. The simulation starts with the primary interactions of various types of hadrons with the silicon atoms, the formation of the interstitials and vacancies in the lattice (see Figure 9) and the calculation of the NIEL. Thereafter the reactions of the vacancies and interstitials with each other (e.g. annihilation) and with the impurities oxygen and carbon (e.g. formation of the VO and V_2O defects) are modeled. Finally, the impact on the depletion voltage and the leakage current of the detector is calculated.

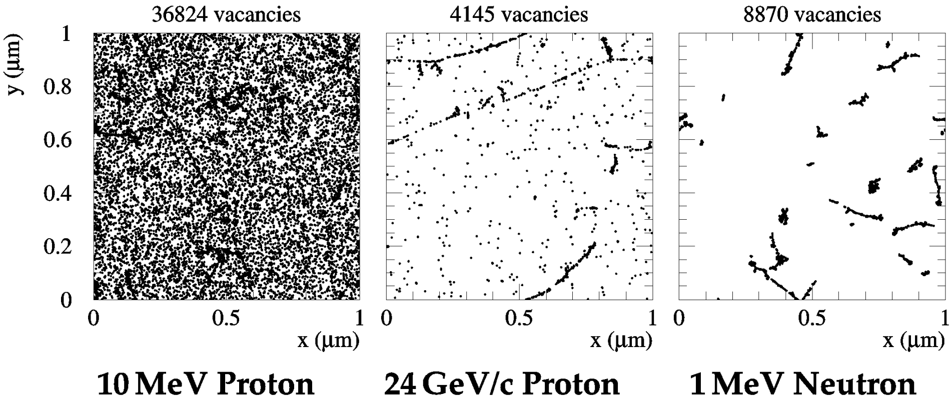

Figure 9: Initial distribution of vacancies produced by different kind of hadrons. The plots are projections over 1µm of depth (z) and correspond to a fluence of 10^{14} cm^{-2}.

Based on these calculations it has been shown that the so-called “proton-neutron-puzzle” of oxygenated and non-oxygenated silicon (see also Section 5.1) can be explained by the presently used models. However, predictions made for the depletion voltage and the leakage current of low energy proton irradiated oxygenated and non-oxygenated detectors using the same modeling have still to be verified although first experimental results seem to agree. Furthermore, some of the defect parameters had to be adjusted in the model, since they so far could not be measured.

The above-mentioned models need as input parameters certain defect properties. These parameters are most often measured parameters. However, not all defect properties can be measured, especially for defects with small concentration compared to the overall defect concentration. Ab-initio calculations have been extensively performed by theoretical solid state physics groups and are now capable to predict the structure, energy level and the charge state of defects [58].

9.2.2 Device Simulation

Recent results achieved with commercial and in-house software packages have helped crucially in understanding the present limitation of irradiated silicon devices. Furthermore, device simulators are an indispensable tool for the development of novel device structures in order to optimize signal formation, charge collection efficiency, signal to noise ratio, power dissipation and device thickness.

10 Work Plan, Organization and Resources

10.1 Work Plan

The range of expertise covered by the institutes which have joined the collaboration spans from theoretical and applied solid state physics, device and material processing, detector systems and detector design to defect and detector simulation. Table 1 summarizes the distribution of research interests as expressed by the collaborating institutes.

Table 1.: Number of institutes interested in the different research fields.

Research Interest	Institutes
Defect Engineering	14
New detector Structure	13
Detector design	9
Detector processing	5
Operational conditions	6
New materials	20
Basic studies – microscopic	21
Basic studies – macroscopic	31
Basic studies – surface damage	1
Radiation studies on full systems	8
Detector simulation	13
Defect modeling	10

This very broad expression of interests and expertise allows proceeding in parallel with the various aspects of our research program. The collaboration will divide into dedicated working groups, which will tackle a particular aspect of the proposed research. In this plan basic studies and simulations will play a substantial role. Following the project covered by this proposal, a follow-up project is suggested where the best performing detector designs and materials, satisfying the specific needs of experiments with sensors subjected to high radiation levels, will be processed and tested with readout electronics.

- **Evaluation of oxygenated silicon**

The understanding of the effect of oxygen and oxygen dimers in silicon will be pursued at the radiation levels foreseen in a high luminosity environment with neutrons, hadrons, electrons and gammas. The tests will include microscopic and macroscopic testing on simple structures under different operational conditions and the data supported by simulations. Simultaneously the existing oxygenated segmented structures, already fabricated for the baseline LHC experiments, will be tested at the same irradiation levels as the simple structures. This test is crucial in order to correlate the microscopic material parameterizations in the presence of segmented electric field distributions and fast electronics and consequently to evaluate the high radiation fluence effect on S/N, power dissipation and signal speed. Emphasis will be given to the effect of radiation under bias and at different operational conditions, for example temperature.

- **Evaluation of other detector structures**

The processing of short drift length design detectors will take place in dedicated laboratories, which are part of the collaboration. The fabricated structures will be distributed to the other interested members of the collaboration, who will then organize irradiation testing and evaluations of their performance. The materials will be selected amongst the ones available to the collaboration and will include oxygenated silicon and other semiconductors, depending on the processing restrictions.

- **Other materials**

The institutes which already have access to other possibly radiation hard materials will act as distributors to the other institutes in order to coordinate a complete systematic evaluation of all the aspects of the technology. These aspects involve the radiation induced defect formation evaluation together with the macroscopic response under different operational conditions. Also in this case, a close integration with fast multi-channel electronics is essential and therefore close contact will be maintained with high-energy physics electronic design groups.

10.2 Timescale

The timescale foreseen to complete the research plan is 3 years.

10.3 Milestones

1st year

- Design and fabrication of common test structures
- Irradiations of simple and segmented structures (oxygenated and non-oxygenated) up to 10^{16} cm^{-2} n, p and very high γ and e doses
- Agreement on post-irradiation detector handling and measurement procedures
- Workshop and 1st status report

2nd year

- Full comparative characterization of simple and segmented structures with oxygenated and non-oxygenated silicon.
- Improved understanding of the “proton/neutron puzzle” and the microscopic mechanisms leading to the beneficial effect of oxygen in silicon.
- Design and fabrication of segmented structures using dimered and CZ silicon and other semiconductor materials
- Design and fabrication of thin and 3D detectors of different resistivity

- Workshop and 2nd status report

3rd year

- Full comparative characterization of above described devices including fast electronics
- Workshop and final report, containing recommendations for:
    - detector material
    - detector structure
    - operational conditions
    - further research and development options

10.4 Organization

The organization of the R&D collaboration will be decided in one of the first meetings of the Collaboration Board and will be written down in a separate document, which will also contain an agreement about the publication policy.

In the following we describe a suggested preliminary outline of the organization, which was discussed during the workshop on "Radiation hard semiconductor devices for very high luminosity colliders", held at CERN in November 2001[31]. Currently the collaboration comprises 231 members from 45 institutes. Given the size of the collaboration and the wide scientific program it is appropriate to split up the collaboration in research teams, which focus on specific activities (see Figure 10).

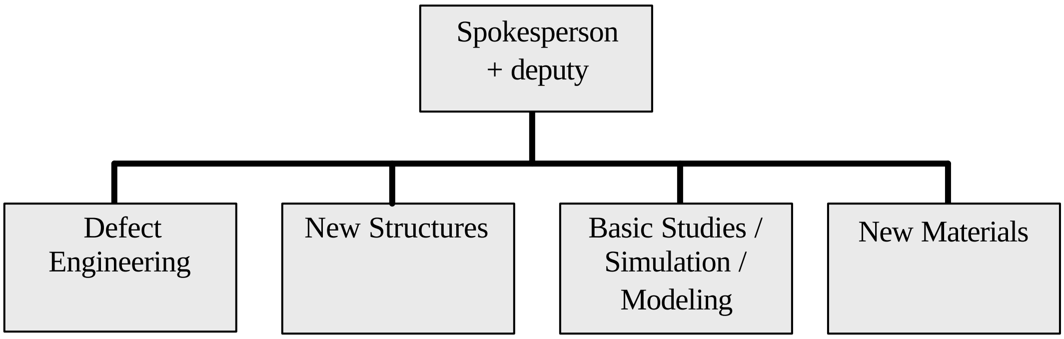

Figure 10: The participating institutes form research teams focused on specific activities. Each team is co-ordinated by a Team Convener.

Each team is co-ordinated by a Research Team Convener. The Spokesperson ensures the overall co-ordination of the research work.

The central decision taking body of the collaboration is the Collaboration Board (CB), in which each institute is represented by one member. As shown in Figure 11, the CB elects a chairperson and a deputy. It also elects the spokesperson and a deputy. The spokesperson nominates the Research Term Conveners and the Budget Holder of the Common Fund, which are appointed by the collaboration board.

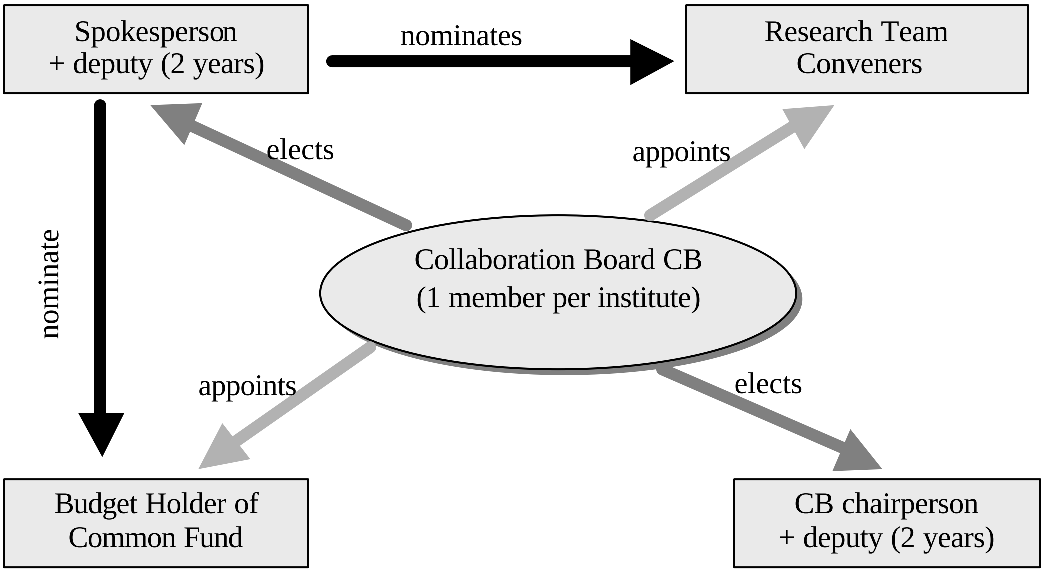

Figure 11: Role of Collaboration Board and Spokesperson within the collaboration structure.

10.5 Resources

All participating institutes are expected to organize their own resources required for the research activities in their home laboratories. Integration in a CERN approved R&D project allows them to apply for national funding in terms of financial and manpower resources. The collaboration comprises several institutes, which have access to irradiation sources (reactors and accelerators), as well as clean room and sensor processing facilities. A very wide range of highly specialized equipment for characterization of sensors and materials is also available. A tabular overview is given in appendix A.

- **Common Fund**

It is planned to set up a low volume Common Fund to which each institute contributes every year a minimum amount. The Common Fund may be used for the organization of collaboration workshops, rental costs (electronics pool), or other specific activities of common interest. For project related investments, like processing of common test structures or purchasing of special equipment, additional contributions may be requested from the institutes participating in the concerned project.

- **Lab space at CERN**

The new R&D collaboration is intending to temporarily use existing infrastructure and equipment at CERN. As a member of the collaboration, the section EP-TA1/SD can provide access to available lab space in building 14 (characterization of irradiated detectors), in building 28 (lab space for general work) and in the future Silicon Facility (hall 186, clean space). In total a surface of about 50 m^2 is required on a temporary basis.

- **Technical support at CERN**

The collaboration intends to use the existing test beams (PS / SPS) and the irradiation facility in the CERN PS complex (24 GeV/c protons and neutrons). The latter is under the responsibility of the section EP-TA1/SD, which can provide the required support (sample preparation / irradiation / dosimetry). EP-TA1/SD is also able to provide support in wire bonding and sensor mounting. The expected work volume is however estimated to be very limited. A low level of support from EP-MIC, EP-ED and EP-ESS may be profitable.

Appendix A

Group-Abbreviation	**Group members**	**Man-year equivalent**	**Defect Engineering**	**New Detector Structures**	**Detector Design**	**Detector Processing**	**Operational Conditions**	**New Materials**	**Basic Studies (microscopic)**	**Basic Studies (macroscopic)**	**Basic Studies (surface damage)**	**Radiation Studies (full systems)**	**Detector simulation**	**Defect modeling**	**Irradiation Facilities**	**Comments**	**other Exp.**
Bari	3		x				x		x	x		x				CV-IV-DAQ-Clean Room	CMS
Bellaterra (Barcelona)	7	1.6		x	x	x		x		x							ATLAS-SCT, ROSE
Demokritos	4	1.3						x	x						n (reactor), γ, p (tandem)	SiC, EPR	ENDEASD, ROSE
Dortmund	5	0.6			x					x	x	x	x		e (20keV)	ISE/TCAD	ATLAS-Pixel, ROSE
Erfurt	2			x	x	x		x								Wafer processing/probing-Modelling/Simulation-Bonding-Glueing	CIS-Company
Exeter	9	7.5	x					x	x					x		Theoretical group, AIMPRO / SiC, GaN, diamond	ENDEASD
Florence	9	5.7			x			x	x	x						TSC, DLTS, PICTS, Hall,… / SiC, diamond	CMS, RD39, ROSE, RD42
Geneva, CERN	3	1.1	x							x					p(23GeV), n(mixed field)	bonding, clean room	ROSE
Glasgow	11	5.3		x				x		x			x			3D / SiC, GaN	RD39, ROSE

Group-Abbreviation	**Group members**	**Man-year equivalent**	**Defect Engineering**	**New Detector Structures**	**Detector Design**	**Detector Processing**	**Operational Conditions**	**New Materials**	**Basic Studies (microscopic)**	**Basic Studies (macroscopic)**	**Basic Studies (surface damage)**	**Radiation Studies (full systems)**	**Detector simulation**	**Defect modeling**	**Irradiation Facilities**	**Comments**	**other Exp.**
Halle	2							x	x							SiC, GaAs / positron annihilation	
Hamburg	7	4.3	x						x	x			x	x		CV-IV-C-DLTS-TCT-SEM-ISE/TCAD/Laser Scanning	SRD
Hawaii	1	1		x												3D	
Helsinki University	4							x		x						CdTe, CdZnTe, Clean rooms, bonding	
Helsinki HIP	6	1.3		x		x			x						p	PCD,SPV / Clean room	CMS
Karlsruhe	4									x					25 MeV Proton	TCT-Probe-Bonding Lorentz-angle	CMS
Kiev	9	2.6							x	x					n(reactor), p(7,50-100MeV), n(14MeV)	Hall, IR	ROSE
Lancaster	6	1.5	x				x			x			x	x		CV/IV(-30C-+80C),CCE(γ,α,mip)	ATLAS-SCT, ROSE
Liverpool	2	0.4										x				Clean room, DAQ (LHC)-Mask design-IV-CV-probe	LHCb, ATLAS
London (Kings)	5	3						x	x					x		FT-PL, IR, EPR	ENDEASD, ROSE
Louvain	3									x					ion,p,n		CMS

Group-Abbreviation	**Group members**	**Man-year equivalent**	**Defect Engineering**	**New Detector Structures**	**Detector Design**	**Detector Processing**	**Operational Conditions**	**New Materials**	**Basic Studies (microscopic)**	**Basic Studies (macroscopic)**	**Basic Studies (surface damage)**	**Radiation Studies (full systems)**	**Detector simulation**	**Defect modeling**	**Irradiation Facilities**	**Comments**	**other Exp.**
Lund	3	0.5							x						e(3-7MeV),γ	IR	
Ljubljana	4	0.8								x			x	x	n(reactor)	TCT	ATLAS, Delphi, RD39, ROSE
Milano	6	1.2					x			x		x	x			clean room, bonding	ATLAS-Pixel
Montreal	5	2.3							x	x			x	x	12 MeV protons	Test benches (diode/pixels)	
Moscow (ITEP)	8	0.7		x					x	x						Avalanche Si det charge amplif, printed circ. Boards (design and production)	
Moscow (Kurchatov)	9	2.1						x	x	x					35 MeV protons, Neutrons, Ions	CV-IV TEM-X-ray-T control	
Oslo	4	2.2					x	x	x	x				x	1 MeV ion tandem (end 2002)	CV-IV-DLTS-Admittance Spectr. Inv Photoemission-PL- Cryogenics-Opt. Interferometry-thin film dep.-Furnaces	
Oulu	5	1.4		x		x				x						CV-IV- DAQ-Tcontrol	
Padova	4	1								x		x			x-ray gun, 28 MeV proton, Heavy ions	Clean room, micro-bonding-IV-Laser pulse-SPICE-ISE-TCAD	

Group-Abbreviation	**Group members**	**Man-year equivalent**	**Defect Engineering**	**New Detector Structures**	**Detector Design**	**Detector Processing**	**Operational Conditions**	**New Materials**	**Basic Studies (microscopic)**	**Basic Studies (macroscopic)**	**Basic Studies (surface damage)**	**Radiation Studies (full systems)**	**Detector simulation**	**Defect modeling**	**Irradiation Facilities**	**Comments**	**other Exp.**
Pisa	4	1			x				x	x		x				CR probe -bonding-DAQ	CMS
Piscataway	4	0.5						x		x				x		Clean room-bnding-processing-DAQ	CMS, RD42,CDF
Prague (CTU+ChU)	13	5			x			x		x				x	p(0.3-2MeV), n(-14MeV)	clean room	RD49, ROSE
Prague (Inst.of Phys)	4	0.5	x	x						x							ATLAS-Pixel, ROSE
St.Petersburg	5	1.9					x	x	x	x			x		p	GaAs / TCT,DLTS	RD39, ROSE, ATLAS-SCT
Surrey	2	1.2						x					x		γ	CdTe,CdZnTe / PL,DLTS,PICTS,..	
Syracuse	5	2			x			x								Clean room- CV-IV-Laser-Pixel prototypes	b-TeV
TelAviv	4		x	x				x	x	x			x			CdZnTe / DLTS,TCT,PSD / ISE-TCAD	ROSE
Trento	6	1	x	x	x	x							x			ISE-TCAD,Silvaco	
Trieste	2	0.5	x	x				x		x			x		e(1GeV)	SiC / ISE-TCAD	BarBar, Alice (microstrip)
Upton (BNL)	1		x	x			x									IV-CV-TCT/TChT Detector design/processing	RD39
Uxbridge (Brunel)	5	4.6	x	x					x	x			x	x	γ	3D / DLTS,..	ENDEASD, RD39, RD49, ROSE-CMS

Group-Abbreviation	**Group members**	**Man-year equivalent**	**Defect Engineering**	**New Detector Structures**	**Detector Design**	**Detector Processing**	**Operational Conditions**	**New Materials**	**Basic Studies (microscopic)**	**Basic Studies (macroscopic)**	**Basic Studies (surface damage)**	**Radiation Studies (full systems)**	**Detector simulation**	**Defect modeling**	**Irradiation Facilities**	**Comments**	**other Exp.**
Valencia	3	0.8								x		x				clean room, bonding	ATLAS-SCT
Villigen-PSI	2	0.3	x		x							x			PSI, pions	bonding	CMS-Pixel, ROSE
Vilnius	9	3.9	x					x	x	x						IV-CV-SIMS-ESCA-AES-DLTS-TSC, free carrier lifetime/mobility, photoconductivity, ….	
Warsaw (ITME)	12	1.5	x					x	x	x						Si-production (CZ,FZ, EPI), GaAs,InP / FTIR, SIMS, DLTS, PITS	ROSE
45	**231**	**--**	**14**	**13**	**9**	**5**	**6**	**20**	**21**	**31**	**1**	**8**	**13**	**10**	**--**		

References

[1] ATLAS – Inner Detector Technical Design Report; CERN/LHCC/97-16,17.

[2] ATLAS – Pixel Detector Technical Design Report; CERN/LHCC/98-13.

[3] CMS – Technical Proposal; CERN/LHCC 94-38

[4] EP-TH Faculty Meeting, CERN, 17.01.2001

[5] M.Huhtinen, "Simulation of non-ionising energy loss and defect formation in silicon" ROSE/TN/2001-02; http://cern.ch/rd48/; to be published in NIMA.

[6] G.Lindström et al. (The RD48 Collaboration); "Radiation Hard Silicon Detectors - Developments by the RD48 (ROSE) Collaboration –"; NIM A 466 (2001) 308-326.

[7] G.Lindström et al. (The RD48 Collaboration); "Developments for Radiation Hard Silicon Detectors by Defect Engineering - Results by the CERN RD48 (ROSE) Collaboration –"NIM A 465/1 (2001) 60-69.

[8] Data taken from: R.Wunstorf, PhD thesis,"Systematische Untersuchungen zur Strahlenresistenz von Silizium-Detektoren für die Verwendung in Hochenergiephysik-Experimenten", University of Hamburg, October 1992.

[9] M.Moll, "Radiation Damage in Silicon Particle Detectors – Microscopic Defects and Macroscopic Properties - ",PhD-Thesis, DESY-THESIS-1999-040, December 1999.

[10] G. Kramberger et al. Effective carrier trapping times in irradiated silicon, Presented at 6-th ROSE Workshop RD48, October 2000, CERN (CERN/LEB 2000-006).

[11] I Gorelov et al., "A measurement of Lorentz angle and spatial resolution of radiation hard silicon pixel sensors" CERN-EP/2001-032; in press on NIM.

[12] The RD2 Collaboration

[13] The RD20 Collaboration

[14] The RD39 Collaboration "Cryogenic tracking detectors"; http://cern.ch/RD39

[15] The RD42 Collaboration "CVD Diamond Radiation Detector Development"; http://cern.ch/RD42

[16] The RD48 (ROSE) Collaboration "**R**esearch and development **O**n **S**ilicon for future **E**xperiments"; http://cern.ch/rd48

[17] The RD49 Collaboration; http://cern.ch/rd49

[18] B. Dezillie et al. "The Effect of Oxygen Impurities on Radiation Hardness of FZ Silicon Detectors for HEP after Neutron, Proton and Gamma Irradiation." IEEE Trans. Nucl. Sci. 47 (2000) 1892-1897.

[19] Z. Li et al., "HTLT Oxygenated Silicon Detectors: Radiation Hardness and Long Term Stability," Nucl. Instr. Meth., A461, pp.126-132, 2001

[20] E.Fretwurst et al.; "Bulk damage effects in standard and oxygen enriched silicon induced by Co-60 gamma radiation" presented in [31].

[21] Z. Li et al.; "Investigation of the Oxygen-Vacancy (A-Center) Defect Complex Profile in Neutron Irradiated High Resistivity Silcon Junction Particle Detectors"; IEEE TNS, Vol 39, No 6, 1730-1738 (1992).

[22] A. Ruzin et al., IEEE Trans. on Nuclear Science, vol.46, no.5, 1310 (1999).

[23] J.Wyss et al.; "Observation of an energy dependence of the radiation damage on standard and oxygenated silicon diodes by 16, 21, and 27 MeV protons"; NIMA 457 (2001) 595-600.

[24] M.Moll et al. ; "Irradiation tests on standard and oxygenated ROSE diodes produced by ST Microelectronics and Sintef", ROSE Meeting on Radiation Hardening of Silicon Detectors, CERN, 16-17 March 2000; Transparencies: CERN/LEB 2000-005, 5th ROSE Workshop, RD48, March 2000, 278-299

[25] M.Moll et al.; "Investigation on the improved radiation hardness of silicon detectors with high oxygen concentration"; NIMA 439 (2000) 282-292

[26] J.Wüstenfeld, Ph.D.thesis University of Dortmund, Internal Report, UniDo PH-E4 01-06, August 2001, see also ROSE/TN/2000-05 in [16].

[27] G.Casse et al.; "A comparative study of oxygenated and non-oxygenated pad diodes, miniature and large area microstrip detectors"; NIMA466:335-344,2001.

[28] D.Robinson et al.; "Comparison of signals obtained from oxygenated and non-oxygenated silicon microstrip detectors after irradiation to $3\cdot10^{14}$p/cm^{2}"; NIMA461:226-228,2001.

---

[29] P.P.Allport et al.; “Radiation Hardness of oxygenated microstrip detectors read out with LHC speed electronics”; IEEE Trans.Nucl.Sci.48:1007-1011,2001

[30] I.Pintilie et al, "Deep trapping level in Co-60 gamma irradiated silicon detectors investigated by C-DLTS", submitted for publication in Applied Physics Letters (presented also in [30])

[31] “1st Workshop on Radiation hard semiconductor devices for very high luminosity colliders”, CERN 28-30 November 2001, http://ssd-rd.web.cern.ch/ssd-rd/rd/

[32] A.Barcz et al.; “SIMS measurement of oxygen in FZ silicon”, presented in [31].

[33] G.Lindstroem et al.; “Preliminary Results of the CiS-Hamburg SRD Project”, presented in [31].

[34] J.L. Lindström et al.;“Oxygen and Carbon Clustering in Cz-Si during Electron Irradiation at Elevated Temperatures”, Solid State Phenomena 70 (1999) 297-302.

[35] M. Moll, H. Feick, E. Fretwurst, G. Lindstrom, T. Schultz, NIM A 338 (1997) 335.

[36] J. Coutinho et al.; “Oxygen and dioxygen centers in Si and Ge: Density-functional calculations”; Phys. Rev. B 62, 10824 (2001).

[37] S.J. Watts and C. Da Via’, presented at the Vertex 2001 Conference, Brunnen Switzerland. To be published in NIMA.

[38] C. Da Via and S.J.Watts, “New results for a novel oxygenated silicon material”, paper submitted to the "European Materials Research Society 2001 Spring Meeting - Symposium B on Defect Engineering of Advanced Semiconductor Devices, Strasbourg, France, June 5-8, 2001, to be published in NIMB.

[39] S. Ramo, Proc IRE 27 (1939) 584.

[40] W.Shockley, Journal of Applied Physics 9 (1938) 635.

[41] G. Cavalleri, et al., NIM 21 (1963) 177 - 178.

[42] G. Cavalleri, et al., NIM 92 (1971) 137 - 140.

[43] Sherwood Parker et al. Performance of 3D architecture, silicon sensors after intense proton irradiation, IEEE Trans. On Nucl. Sci. 48 (2001) 1629-1638 and references therein.

[44] K. Abe et al.; “Design and performance of the SLD vertex detector: a 307 Mpixel tracking system”, NIM A 400 (1997) 287-343.

[45] P.Gerlach et al.; IEEE-Transactions-on-Nuclear-Science. vol.47, no.3, pt.2; June 2000; p.745-9.

[46] K.Borer et al. ; “Charge collection efficiency of irradiated silicon detector operated at cryogenic temperatures”, NIMA 440, 2000, 5-16

[47] L. Beattie et al NIM A439 (2000) 293-300.

[48] M. Rogalla et al. Nucl Phys. B Proceedings Supplements 78 (1999) 516-520.

[49] C. Hordequin et al, NIMA 456 (2001) 284-289.

[50] LCFI Homepage : http://hep.ph.liv.ac.uk/~green/lcfi/home.html

[51] M.A.Kozodaev et al.; “STM analysis of surface phenomena in Si(1 0 0) under proton irradiation”, Ultramicroscopy, Volume 82, Issues 1-4, February 2000, 111-117

[52] A.Schweiger and G.Jeschke, “Principles of pulse paramagnetic resonance”, Oxford University Press 2001

[53] G.Mitrikas et al.; “EPR studies of neutron-irradiated n-type FZ silicon doped with tin”, accepted for publication in NIM B.

[54] V.Cindro et al.; ”Bias-Dependant Annealing of Radiation Damage in Neutron-Irradiated Sillicon p+-n-n+Diodes”; NIMA419 (1998), 132-136.

[55] V. Bartsch et al.: “An algorithm for calculating the Lorentz angle in silicon detectors”, submitted for publication in NIM A.

[56] B.C. MacEvoy, et al, Defect kinetics in Novel Detector Materials. Presented at the 1st ENDEASD Workshop, Santorini, April 21-22 1999. Accepted for publication in Materials Science in Semiconductor Processing.

[57] Mika Huhtinen; “Simulation of defect formation in different hadron irradiation environments”, presented in [31].

[58] The AIMPRO group; http://aimpro.ncl.ac.uk/