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RADIATION DAMAGE IN Si MICROSTRIP DETECTORS

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Abstract: Radiation damage in silicon microstrip detectors will play an important role in the design of tracking devices at future high luminosity experiments. Overview of macroscopic effects is given. Increase of leakage current, change of depletion voltage and decrease of charge collection efficiency are the most important effects, however operation after irradiation with few 10^{14} particles cm^{-2} is still possible.

Radiacijske poškodbe v mikropasovnih detektorjih

Ključne besede: polprevodniki, komponente silicijeve, Si detektorji mikrotrakasti, poškodbe vsled sevanja, poškodbe vsled obsevanja, napake vsled sevanja, obsevanje detektorjev, merjenja preskusna, instrumenti jedrski, HEP fizika energij visokih, odpornost proti sevanju, poškodbe vsled ionizacije, sevanje ionizirajoče, NIEL izguba energije neionizirajoče, PKA atomi izbiti prvotno, LHC trkalniki hadronski veliki, FDV napetost osiromašenja polnega, CV metoda kapacitivnost-napetost, CCE izkoristek zbiranja naboja

Povzetek: Radiacijske poškodbe v mikropasovnih detektorjih so pomembne pri načrtovanju sledilnikov nabitih delcev v prihodnjih eksperimentih z visoko luminoznostjo. Podan je pregled makroskopskih posledic, ki jih povzročijo delci.
Glavne posledice so: porast mrtvega toka, sprememba napetosti, potrebne za osiromašenje detektorja in zmanjšanje učinkovitosti zbiranja naboja. Rezultati meritev so pokazali, da je sledenje nabitih delcev možno tudi po prehodu več kot 10^{14} delcev cm^{-2}.

1. Introduction

Silicon microstrip detectors became a common tool in high energy physics experiments after introduction of planar technology on low resistivity silicon for production of silicon devices /1/. This technology allows segmentation of the junction and the use of the segments to determine particle positions. In microstrip detectors these segments are narrow strips with widths around 100 microns. Each of them represents a p-i-n diode, which is then used to detect the traversal of an ionizing particle through silicon. Commonly, p strips are produced on n bulk material yielding single sided segmentation and detection of particle position in one dimension. Double sided detectors, having strips on p and n sides, have been also produced and used in experiments /2,3/.

To make use of the high resolution of microstrip detectors for tracking, the precision should not be compromised by multiple Coulomb scattering. Therefore it is important to have thin detectors. The normal thickness of existing detectors is about 300 microns determined by the practical limit of processing 4-inch wafers. In addition, the signal for high energy particles is proportional to the detector thickness. Therefore a further reduction of detector thickness would degrade the signal. For applications with a large number of detection channels a sufficient signal to noise ratio is critical for a good position resolution and low background occupancy.

Detector development has been accompanied by the development of readout electronics. Low noise and power, and large density of input channels are the main constraints for the chip design. For microstrip detectors, various strip pitches have been used, depending on the resolution requirement /4,5,6/. Currently 25 micron readout pitch is a practical limit in detector fabrication. With that, a few micron position resolution has been achieved in a test beam.

Most currently running colliding beam experiments have a large vertex detector made of several layers of silicon microstrip detectors /4,5,6/. Radiation in existing experiments does not cause any significant damage to the detectors and several years of running time could be achieved without considerable degradation in the detector performance. However, the new experiments in construction (HERA-B at DESY, Hamburg and ATLAS, CMS at LHC, CERN, Geneva) at high-rate and energy proton accelerators will put new requirements to the radiation hardness of detectors. Particle fluences and the associated radiation dose will by far exceed that encountered by any existing tracking detector. The area covered by detectors will be in the order of few ten m^2 and the number of channels will be of the order of 10 million. Unlike the existing detectors, there is little prospect of replacing them during the lifetime of the experiment (~ 10 years) and maintenance access for repairs will be restricted. Therefore the detectors should be sufficiently radiation hard to survive in the hostile environment during the whole data taking period. Radiation hardness of readout electronic is a separate problem, studies may be found elsewhere /7/.

2. Radiation effects

The effects of radiation to silicon microstrip detectors may be divided into two categories. The surface damage depends on detailed processing steps and on detector design, while the bulk damage relates to generic properties of the crystal itself.

Surface damage is caused by ionizing radiation (e.g. electrons, γ rays) causing irradiation damage by ionization in the silicon dioxide layer and at the Si-SiO_2 interface. The charge built up due to holes being trapped in the oxide causes an increase of the electron density in the accumulation layer at the silicon surface. Ionizing radiation doses expected at future experiments are of the order of 100 kGy (10 Mrad). Interstrip resistance and capacitance measurements are used to estimate the damage of ionization to microstrip detectors. Measurements of the CERN RD-20 collaboration have shown only a slight (20-30%) increase of the capacitance, saturating at doses higher than 10 kGy (Figure 1., from ref. /8/). This effect is tolerable in future applications, since it would only marginally increase the electronic noise - depending on detector size. The same collaboration measured the ionizing radiation effects on n sided detectors. With a proper design of the interstrip isolation /9/, radiation resistance was achieved.

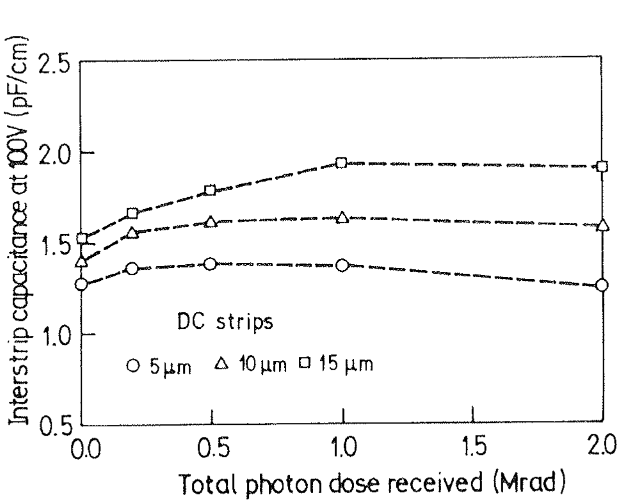

Fig. 1: Interstrip capacitance at 100V, 1 MHz as a function of photon dose /8/.

Bulk damage in Si lattice causes more concern to future high energy physics applications. The ionization energy loss in silicon bulk is a reversible process in itself (electron-hole pairs recombine) and causes no durable defects. However, due to the interaction of the radiation with silicon atoms the periodic structure of the lattice is destroyed locally, i.e. silicon atoms are dislocated. The displacement damage in the silicon bulk corresponds to the non-ionizing energy loss (NIEL). Lattice atoms displaced by incoming particles are termed primary knock-on atoms (PKA). An average energy E_d of about 25 eV /10/ is required to dislocate a PKA. The maximum energy transferred from a particle of energy E_n to a silicon atom can be deduced from collision kinematics:

$$E_{max} = 4\, E_n\, M_n\, M_{Si}/(M_n + M_{Si})^2$$

where M_n and M_{Si} are the incoming particle and Silicon atom masses, respectively. More energy is transferred for heavy particles than for light ones. For example, for 1 MeV neutrons E_{max} = 130 keV, while for 1 MeV electrons E_{max} = 120 eV only. Therefore, heavy particles are causing considerably more displacement damage to the bulk. If more than Ed energy is transferred, the PKA will lose the surplus of energy by ionization or further displacements of lattice atoms which may proceed in a cascade manner. Consequently, from a primary PKA, a number of vacancies (V) and interstitial (I) atoms are created along its path, forming a cluster. In the interior of the cluster, where initial concentrations of vacancies and interstitials are high, direct recombination occurs and most I-V pairs annihilate on a very short time scale. Those that do not get annihilated may move to the surface or form relatively stable complex defects. Interstitial atoms diffuse out from clusters more rapidly than vacancies. So the main known complex defects are vacancy-related: the divacancy (V-V), the silicon E centre (V-P) composed of a vacancy and phosphorus atom in adjacent lattice positions, and the silicon A centre (V-O) composed of an oxygen atom and a vacancy. The actual ratio of defects formed depends on the concentration of impurities present in the silicon.

Non ionizing energy loss per unit length may be calculated from:

$$(dE/dx)_{NIEL} = \rho\, N/A \int E_r\, d\sigma/dE_r\, L(E_r)\, dE_r$$

where ρ is density, N and A are Avogadro's number and the atomic weight of silicon, $d\sigma/dE_r$ is the differential cross section to produce a recoil fragment with energy E_r and $L(E_r)$ is the fraction of this energy which appears as NIEL at the particular recoil energy E_r /11/. Extensive calculations have been performed for silicon /12,13,14/ for various particles (Fig. 2).

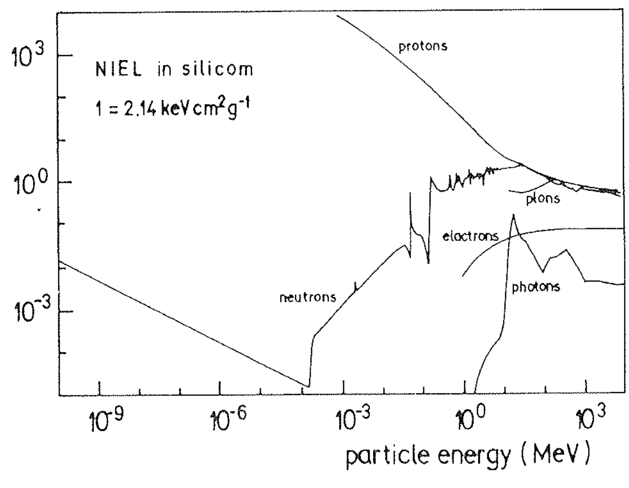

Fig. 2: NIEL data for use in detector damage projections

Study of bulk defects and predictions for future applications are obscured by the fact that most of the damage to the detectors will be caused by pions and neutrons, while irradiation studies of detector performance have been done predominantly with neutrons and protons. In order to allow a universal comparison of results it is common practice to refer damage to the equivalent fluence of 1 MeV neutrons which would have caused the same NIEL as the fluence really applied. As a standard, $(dE/(\rho.dx))_{NIEL} = 2.14$ keV cm^2g^{-1} is usually assumed for 1 MeV neutrons. Measurements up to now have generally confirmed that, within the accuracy of calculations, NIEL adequately reproduces the dependence of bulk damage on particle type and energy.

3. Macroscopic effects

Microscopic defects produced by bulk damage manifest themselves as a change of macroscopic behavior. There are three important effects for microstrip detectors: increase of reverse current, change of depletion voltage and degradation of charge collection efficiency. In high energy physics experiments it is very important to have the efficiency of charged particle detection as high as possible. All of the above mentioned macroscopic effects deteriorate detector performance.

3.a. Increase of leakage current

The increase of leakage current with particle fluence Φ is commonly described by:

$$\Delta J = \alpha\Phi$$

where ΔJ is the difference of current density before and after irradiation, and α is the current damage constant. The microscopic explanation of the constant alpha relies on proportional production of current generation centres to the fluence. The radiation induced current reduces after irradiation due to self annealing of defects, with several different time constants /15/.

$$\alpha = \sum_i \alpha \exp(-t/\tau_i) + \alpha_\infty$$

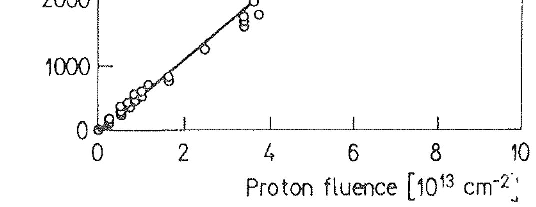

Fig. 3: The change in volume leakage current (normalized to 20°C and corrected for self annealing) versus proton fluence /16/.

The range of time constants τ_i at room temperature is from a few minutes to a few days. The constant part of the leakage current increase has a value

$$\alpha = 4\ 10^{-17}\ A\ cm^{-1}$$

at room temperature and represents roughly 40 % of the initial increase.

In order to compare measurements taken at different times it is important to correct for annealing. Figure 3 /16/ shows that the change in the leakage current is linear with fluence over two orders of magnitude. There is almost no difference between different resistivity n-type ad the p-type detectors. Measured current densities have shown that we may expect high leakage currents after 10 years of running experiments at LHC. One obvious way to reduce the current and its effect is to cool down the detector. This reduces the electronic noise and the probability of thermal runaway of detectors. Therefore it is foreseen to cool down the detectors to about -10°C during operation.

3.b. Change of the depletion voltage

The depletion voltage is an important parameter for running silicon microstrip detectors, the practical limit due to electrical breakdown of detectors and safety aspects in large experiments being about 500 V. It is essential to be able to bias the detectors above the full depletion voltage, otherwise some of the signal created by charged particles would be lost. Therefore microstrip detectors are usually made on high resistivity silicon wafers (resistance few kΩ cm and higher) in order to have a low depletion voltage. However during the irradiation new defects are created and the effective doping concentration (N_{eff}) changes, resulting in a change of the full depletion voltage (FDV). Neff and FDV are related by:

$$|N_{eff}| = 2\ FDV\ \varepsilon\ \ \varepsilon_{Si} / (q\ d^2)$$

where epsilon is the dielectric constant, q the elementary charge and d the detector thickness.

FDV (and thereby N_{eff}) may be determined by different methods, for example measuring the pulse-height spectrum of charged particle signals (charge collection) or the detector capacitance value as a function of the bias voltage. The latter method (CV) has been adopted as a standard technique for FDV evaluation in irradiation studies.

N_{eff} has been measured for various bulk materials and at different particle fluences. A non-linear change of Neff measured on biased detectors can be observed for both n and p type materials at fluences below 10^{13} while at larger fluences Neff increases linearly. For low resistivity n starting material $|N_{eff}|$ drops close to zero and then increases with fluence (Figure 4, from /17/) thus changing the n-type silicon to p-type material. The latter effect is explained as generation of acceptor-like states in proportion to the fluence. It has to be noted that only the effective space charge changes from positive to negative. If the resistivity, i.e. the density of electrons and holes, is measured in thermal equilibrium, silicon is found to become intrinsic with increasing fluence and the Fermi level adjusts close to mid-gap /18/. Experimental evidence for the type inversion behaviour is given by charge collection measurements which have shown that the space charge region starts to grow from the n side of the detector after type inversion /19/.

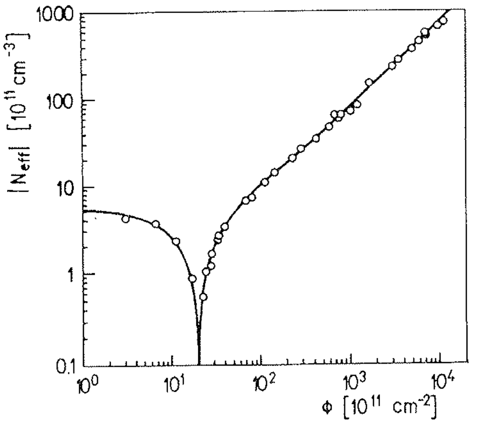

Fig. 4: Change of effective impurity concentration for 1 MeV normalized fluences /17/.

An explanation for the behaviour at lower fluences has not been generally adopted yet. There are two possible explanations. The first is primary donor (substitutional P) and acceptor (substitutional B) removal, and new acceptor creation /20/ while the second explanation assumes deep-level acceptor creation only /21/.

Donor removal could proceed through creation of V-P or C-P defects, which both have high annealing temperatures (~400 K, /22, 23/), and acceptor removal through the reaction $Si_i + B_s > B_i + Si_s$. Interstitial boron is known to be electrically inactive /24/, so acceptors are removed via this reaction by interstitial silicon atoms, produced by irradiation.

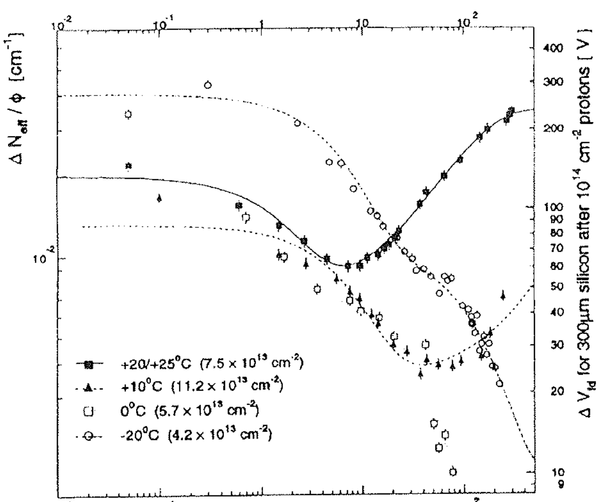

Fig. 5: Evolution of effective impurity concentration and depletion voltage normalized to proton fluence as a function of time after irradiation for detectors kept at the temperature indicated /15/.

The deep acceptor model just assumes creation of an acceptor level close to the mid-gap. Using the measured values of current density with fluence and occupancy from Shockley-Read-Hall statistics, a qualitative agreement with measured depletion voltages was found /21/ by adjusting the introduction rate of the acceptor state as a free parameter.

The time evolution of the depletion voltage has been measured (Figure 5 from /15/) at different temperatures. It may be noticed that two different processes are present. Annealing - reduction of N_{eff} after irradiation - is followed by reverse (long-term) annealing. Annealing may be explained as a first order process involving a dissociation of defects. The dissociation rate is proportional to their concentration resulting in an exponential time behaviour. More complicated and less understood is the reverse annealing process. In the case of two homogeneously distributed defects with concentrations N_{X1} and N_{X2}, which combine to a defect complex Y the creation rate is:

$$-dN_{X1}/dt = -dN_{X2}/dt = k\, N_{X1}\, N_{X2}$$

where k is reaction constant. If $N_{X1} << N_{X2}$ the equation reduces to the first order

$$N_Y(t) = N_{X1o}\,(1 - \exp(-k\, N_{X2}\, t)),$$

N_{X1o} being the defect concentration at $t = 0$, while if $N_{X1} = N_{X2}$ the reaction is of second order

$$N_Y(t) = k\, N_{Xo}^2\, t \,/\, (1 + k\, N_{X1o}\, t)$$

The main difference in time behaviour between first and second order reactions is the dependence of the characteristic time on the initial concentration for the second order. Good agreement for time dependence was found by fitting the measured data with a second order fit /25/.

Acceptor removal by irradiation may explain such behaviour. If interstitial Boron, which is electrically inactive, combines with a vacancy to produce substitutional Boron, a shallow acceptor is regenerated. This results in a decrease of bulk resistance and increase of depletion

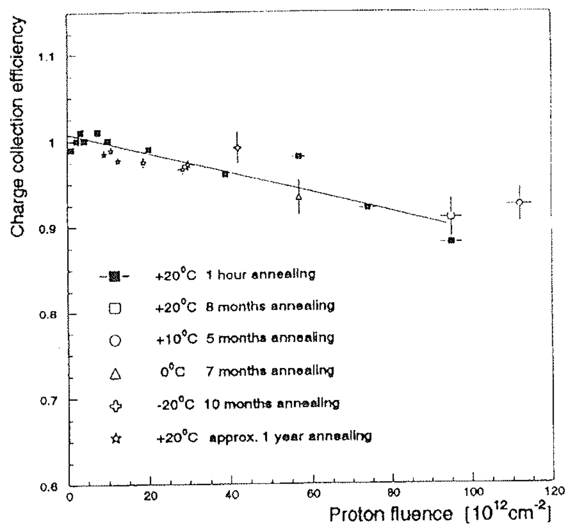

Fig. 6: CCE for relativistic electrons and for collection time of 20ns as a function of proton fluence /15/.

voltage with time. Both effects were confirmed by measurements /20/.

For detectors used at LHC experiments both annealing and reverse annealing have to be taken into account. The reverse annealing time constant strongly depends on temperature. This represents an additional argument for maintaining the detectors below 0°C since it effectively hibernates the reverse annealing process.

3.c. Charge collection efficiency

The charge collection efficiency (CCE) is defined as the charge collected for irradiated detectors normalized to the value measured before irradiation. In addition to the fact that it is sometimes impossible to fully deplete the detector after irradiation, due to the high voltages needed, additional trapping of charge may occur. This is caused by trapping centres produced by NIEL in the silicon. Charge collected by the readout electronics is therefore reduced since the charge trapped is not seen in the signal if detrapping does not occur within the time short compared to the shaping time of the readout electronics. The few existing data for detectors irradiated to 10^{14} particles/cm^2 /12,15/ with electronics having shaping times of about 20ns show that a CCE of 90 percent is still maintained (Fig. 6 from /15/) above the full depletion voltage.

4. Conclusions

A lot of research has been done in recent years in order to estimate possible radiation defects in silicon microstrip detectors after 10 years of operational time at future HEP experiments. Depletion voltages in excess of a few hundred volts have been identified as the main problem for stable operation of microstrip detectors at a large scale. All irradiations of detectors in test measurements have been done at at least two orders of magnitude shorter time than the actual running time of future experiments. A clear microscopic picture for the damage and reverse annealing is also not complete yet. Since radiation defect production and time evolution may still depend on the flux rate and temperature, still more work is needed in the next years if reliable predictions are to be made.

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