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Measurements of charge collection efficiency with microstrip detectors made on various substrates after irradiations with neutrons and protons with different energies

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The possibility of improving the lifetime of silicon detectors operated in high radiation environment using different substrate materials has been investigated for many years. The idea behind this research was that the different contents of impurities of the various substrates could influence the degradation rate of the electrical properties of the sensors. The requirement of relatively low initial full depletion voltage limits the choice of the substrate type that can be investigated to high resistivity crystals. Typically, Floating Zone (FZ) silicon with > 2 kΩ cm resistivity has been used. Recent advancements in crystal growth technology have allowed the production of high resistivity silicon ingots by mean of the Magnetic Czochralski (MCz) method. We investigated the radiation tolerance of microstrip silicon sensors made with n and p-type MCz and FZ silicon crystals by comparing their charge collection properties after various doses of neutron and proton irradiation. The fluences were well in the range of the expected doses for the microstrip and pixel detectors envisaged for the upgrade of the Large Hadron Collider (LHC) at CERN. Besides, the radiation flux at the SLHC will be composed by a mix of backscattered neutrons from the calorimeter region, with an average energy spectrum of 1MeV, and fast charged hadron emerging from the interactions. The ratio between neutral and charged particles will be equal at about 22 cm radius, with neutrons (charged particles) becoming dominant for larger (smaller) radii. The effect of mixed irradiation on the different silicon substrates has been here studied, showing that n-type MCz silicon exhibit significant advantages in term of radiation hardness with respect to the more standard FZ substrates.

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[1] Speaker

1. Introduction

The upgrade of the CERN-LHC accelerator (SLHC) will aim to an unprecedented luminosity close to $10^{35}cm^{-2}s^{-1}$ [1]. As a consequence of the tenfold increase with respect to the luminosity of the LHC, the vertex and tracker detectors of the present experiments will have to be replaced. Many aspects of the geometry of the new detectors (granularity, number and position of the barrel layers,….) will be dictated by dedicated simulations aimed to optimise the layout for physics performance. It is though already evident that the silicon detectors in the inner radii will be exposed to radiation levels about an order of magnitude greater than within the present LHC. The development of silicon devices able to operate efficiently after doses in excess of 10^{16} cm^{-2} is the challenge for the future SLHC in term of radiation hardness.

2. Irradiation facilities and comparison of the radiation damage

The damage produced by the impinging radiation to the silicon crystal depends on the particle type and energy. The damage to the crystal can be correlated, independently on the radiation, to the energy transferred to the lattice in non ionising interactions (non ionising energy loss, NIEL [2]). Using the NIEL factor to weight the radiation damage of different particles and energies, it is possible to refer the irradiation fluences to a given monochromatic particle. It is a well accepted practice, in high energy physics experiments, to express the hadron radiation doses in 1MeV neutron equivalent (n_{eq}) fluence.

In the experiments at the CERN LHC and future SLHC the radiation damage will be mainly caused by backscattered neutrons from the calorimeter region and by charged particles emerging from the interactions. At larger radii the neutrons will be the dominating contribution to the damage, while at shorter ones charged hadrons will be the primary cause of the degradation of the detectors [3]. The radius at which these contributions are equal is about 22 cm. It has been found that the changes of some electrical properties are different for NIEL equivalent doses of protons and neutrons. For example, the degradation of the full depletion voltage (V_{FD}) with fluence can be reduced in oxygen enriched silicon detectors irradiated with protons, while no influence has been found with neutrons [4,5]. This has to be taken into account during the R&D phase for detectors to be used in a mixed radiation environment such the SLHC. The sensors should be characterised after both proton and neutron irradiations, and, ideally, after the appropriate mix of both particles.

The detectors used for the research here reported have been irradiated in three different facilities.

The IRRAD-7 [6] installation at the CERN-PS in Geneva provides 24GeV/c protons with a flux of 1-3×10^{13} p/cm^2/hour, over an area of about 2×2 cm^2. Protons at this energy can well represent the type of damage generated in silicon detectors from the charged particles emerging from the interactions at SLHC. The intensity of this source only allows reaching 1×10^{16} n_{eq} cm^{-2} after 1000-300 hour's irradiation time. To systematically study detectors irradiated with charged hadrons to the levels required for the pixel sensors (up to 2×10^{16} n_{eq} cm^{-2}), a higher intensity source should be identified.

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The Compact Proton Cyclotron of the University of Karlsruhe [7] can provide 26MeV protons with a flux of 6×10^{14} n_{eq}/cm^2/hour over a surface of 10×10 cm^2. This source can reach SLHC pixel sensor doses within a day of operation. A comparison between the charge collection properties of detectors irradiated to the same NIEL equivalent fluence with the Karlsruhe and IRRAD-7 facilities was carried out to verify that a similar degradation was induced by the two different energy protons.

The neutron irradiations took place at the TRIGA Mark II research reactor of the Jozef Stefan Institute of Ljubljana [8], with a tuneable neutron flux up to 1.8E16 n/cm^2/hour. Lower intensities have been used for good accuracy of the dosimetry, still keeping irradiation time between 1 to 10 minutes.

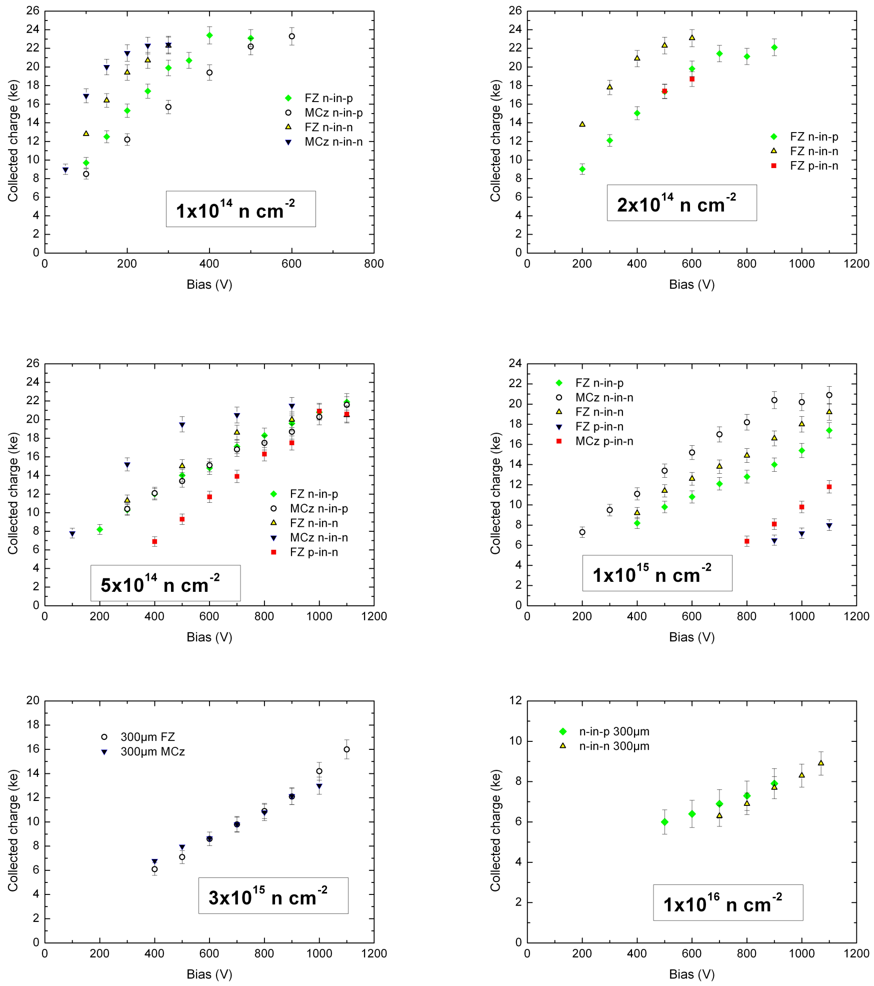

Fig. 1 Charge collection versus bias voltage (CC(V)) for n and p-type FZ and MCz detectors after various neutron fluences from 1 to 100×10^{14} n_{eq} cm^{-2}. P-in-n FZ and MCz detectors have been irradiated to a maximum of 1×10^{15} n_{eq} cm^{-2}, exhibiting much bigger degradation than n-side readout ones. The n-MCz detectors have been irradiated to 1×10^{15} n_{eq} cm^{-2}, showing remarkable improvement with respect to other n-side readout sensors. About 8ke can still be collected by n-in-p sensors after 1×10^{16} n_{eq} cm^{-2}.

3. Different types of silicon p-type substrates

The silicon detectors presently used in high energy physics applications are made with high resistivity, high purity FZ silicon to keep a low initial full depletion voltage. Refinements of the standard Czochralski (Cz) method for growing silicon single crystal that used a magnetic field (Magnetic Czochralski, MCz [9]) to reduce the content of impurity in the final ingot allow for relatively high resistivity (1-2kΩ cm). It is than possible to use these alternative silicon substrates instead of the high purity FZ, with the aim that the different content of various impurities (C, O) can provide a better radiation tolerance [10]. It has been shown that some impurities (in particular oxygen) can have a positive effect in improving the radiation tolerance of silicon detectors [4,5]. It has been suggested that the higher oxygen content of the MCz crystals could lead to better radiation hardness with respect to FZ silicon [11] and several studies have already been performed on this material (see e.g. [12-15]).

N and p-type silicon substrates have been used to produce microstrip detectors with two different readout geometries: n-side and p-side readout. It has been reported that n-side readout can yield a significant enhancement of the radiation hardness of silicon sensors after severe hadron irradiation [16-18]. The comparisons between n and p-side readout here shown confirm this result.

4. Experimental results

It has been reported that the measured full depletion voltage (V_{FD}) of both n and p-type FZ and MCz substrates changes at different rates with neutron irradiation. In particular, the V_{FD} of MCz substrates increase about 55V for every 10^{14} n_{eq} cm^{-2}, compared to 125V in the case of FZ crystals [13]. In particular, a clear advantage is seen with the n-MCz substrate, which combines the lower degradation slope (similar to that for p-MCz) with a much lower initial V_{FD} (due to the higher resistivity) and with the further advantage of seeing the V_{FD} decreasing at low fluences until type inversion. It is in fact well established that neutron irradiation introduces acceptor-like defects that causes conductivity type inversion in n-type silicon (see e.g. [4,5,19]), while they add to the initial concentration of acceptor in the case of p-type silicon. As a consequence, the V_{FD} of the n-MCz after type inversion is about 500V lower than p-MCz after a similar dose, in spite of the same degradation rate with fluence. A similar effect is seen with n and p-type FZ substrates, where a constant difference of about 100V is expected after type inversion (occurring at a few times 10^{13} n_{eq} cm^{-2}). The V_{FD} was evaluated by mean of the capacitance-voltage characteristic of the irradiated detectors. It can only be applied up to about 10^{15} n_{eq} cm^{-2} because after this dose it becomes so high that the direct measurement is not possible. In any case, the most direct evaluation of a silicon detector after irradiation is the measurement of the height of the signal induced by crossing ionising particles. Miniature ($1\times1cm^2$) microstrip detectors with 128 strips, 1 cm long with 80µm pitch have been designed by the University of Liverpool and produced by Micron Semiconductor UK. N and p-type FZ and MCz substrates have been used, and n (n-in-p and n-in-n geometries) and p-side (p-in-n) readout have been implemented. P-spray interstrip isolation has been used in the case of n-side readout.

The detectors have been characterised after irradiation in term of the charge collected as a function of the bias voltage (CC(V)). The charge was deposited by fast electrons from a radioactive source (^{90}Sr). The readout was performed by a SCT128 analogue chip clocked at 40MHz (LHC speed) and the energy spectrum recorded by a flash ADC. The trigger was provided by a plastic scintillator shielded by a 2mm plastic foil to cut the low energy part of the beta spectrum from the ^{90}Sr and coupled to two photo multipliers (in order to reduce the frequency of noise hits in the system). The spectrum obtained mimics the energy deposition of a minimum ionising particle (mip). The CC(V) curve draws the most probable value of the mip energy spectrum as a function of the bias voltage. The system was calibrated with a non irradiated 300µm thick sensor with a known most probable value of 24000 electrons.

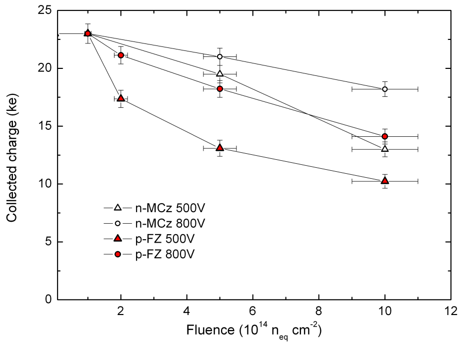

Fig. 2 Degradation of the collected charge with neutron fluence for n-MCz and p-FZ detector at 500V and 800V bias voltage.

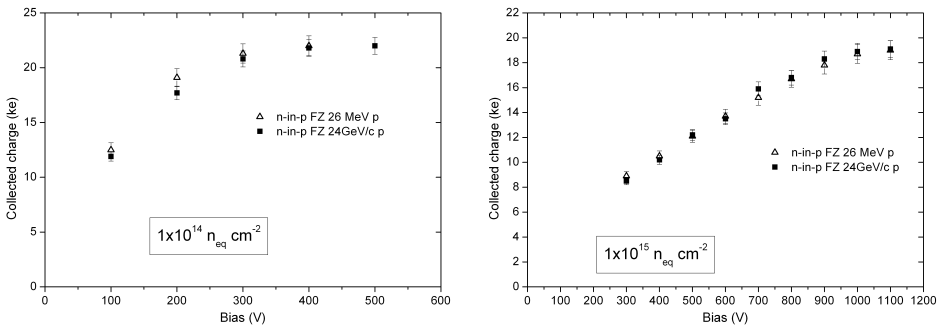

Fig. 3Comparison of the CC(V) of p-FZ detectors irradiated to the same n_{eq} doses with 26MeV and 24GeV/c protons .

Figure 1 shows the CC(V) after neutron fluences over two order of magnitudes, from 1×10^{14} to 1×10^{16} n_{eq} cm^{-2}. The effect of the substrate type and of the readout geometry is evident. The CC(V) of p-in-n devices is similar to the n-in-p up to 2×10^{14} cm^{-2}, but it shows already a significant degradation at low bias voltages after 5×10^{14} cm^{-2} and a much lower efficiency after 1×10^{15} cm^{-2}. Concerning the substrate types, the CC(V) of the n-type detectors (MCz and FZ) irradiated to 1 and 5×10^{14} cm^{-2} rises faster than for the p-type ones, reaching the same saturation charge but at lower bias voltages. The MCz substrate appears to yield the best CC(V) performances. This still seems to reflect the differences found in the V_{FD} changes with neutron irradiation. After 1×10^{15} cm^{-2} only the MCz sensor appears to saturate the CC(V) below 1000V. At higher doses, only the comparison between n and p-type FZ is available. After 3 and

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$10{\times}10^{15}$ cm^{-2} no substantial difference between the two substrates is measured, and no effect of a lower V_{FD} for the n-type sensor is measured. It should be noticed that a remarkable signal of about 8000 electrons is measured after the highest fluence!

Figure 2 shows the degradation of the charge collected at 500V and 800V with neutron fluence by p-type FZ and n-type MCz detectors, showing the better performances with the latter substrate at least up to $1{\times}10^{15}$ cm^{-2}.

Figure 3 shows the comparison of the charge collected by similar p-FZ microstrip detectors irradiated to 1 and $10{\times}10^{14}$ n_{eq} cm^{-2} with 26MeV and 24GeV/c protons. The CC(V) characteristics are in a very good agreement, indicating that the damage introduced by both irradiations is similar. This result will require further studies to assess the effect of the annealing during irradiation. In fact, the irradiation at the Cyclotron of the University of Karlsruhe take place at a temperature below 0^{o}C during a few hours, while at the CERN-PS they are performed at room temperature during a few days. The study of a possible effect on the CC(V) measured at the end of the irradiation introduced by the different irradiation conditions is planned to refine the comparison.

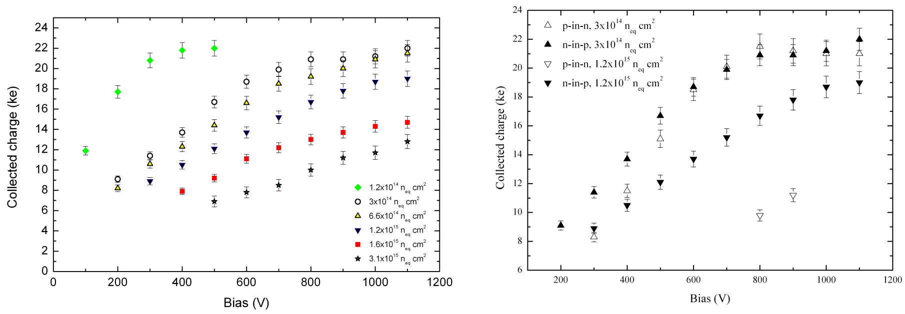

Fig. 4 Changes of the CC(V) of n-in-p detectors after different doses of 24GeV/c proton irradiation (left). Comparison of the CC(V) of n-in-p FZ and p-in-n MCz after two doses of proton irradiation. Significant lower CC(V) is measured with the p-in-n geometry.

Figure 4 shows the degradation of the CC(V) with 24GeV/c proton irradiation. N-in-p FZ detectors were irradiated up to $3.1{\times}10^{15}$ n_{eq} cm^{-2}. After this high dose, about 12000 e^{-} are still collected at 1000V bias. Figure 4 also shows the comparison of the charge collected by n-in-p FZ and p-in-n MCz detector after 3 and $12{\times}10^{14}$ n_{eq} cm^{-2}. The CC(V) is still comparable at the lower dose, but it degrades significantly at the higher one.

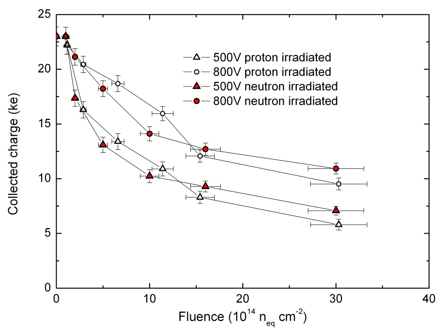

Fig. 5 Degradation of the collected charge as a function of neutron and proton irradiations for p-FZ detector biased at 500V and 800V.

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Figure 5 shows the degradation of the collected charge at 500V and 800V bias after equivalent doses of neutron and proton irradiations. It can be noticed that for fluences below 1.5×10^{15} n_{eq} cm^{-2}, the charge collected by the proton irradiated sensors is higher than the neutron irradiated ones, at corresponding bias voltage and equivalent dose. The opposite behaviour is measured at higher doses. It is known that the increase rate of the V_{FD} with neutron is faster than with proton irradiations. On the other hand, proton irradiations seem to introduce a higher charge trapping with respect to neutrons [20]. The higher charge collected by the proton irradiated detectors at lower doses could depend on a stronger electric field under the collecting electrodes due to a lower value of the V_{FD}. At higher fluences, this effect disappears. The charge trapping becomes dominant, and its lower degradation rate with neutron irradiations allows a better CC(V) with respect to proton irradiated sensors.

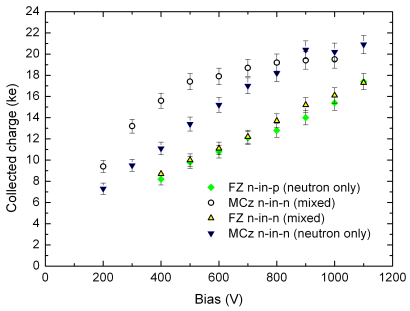

Fig. 6. CC(V) of n-in-n and n-in-p FZ and n-in-n MCz detectors irradiated with neutron only or with an equal dose of neutrons and 26MeV protons to the same total dose of 1×10^{15} n_{eq} cm^{-2}. The compensation effect of acceptor and donor-like defects introduced by the two different type of radiation in the n-MCz substrate is visible in the faster rise of the CC(V) in the case of mixed irradiation.

As already mentioned, the radiation environment in LHC and SLHC will be composed by neutron and charged particles. It has been found that these two types of radiation introduce a different ratio of donor (n-type) or acceptor (p-type) defects on different silicon crystals [21]. In the case of FZ sensors, both radiations introduce predominantly p-type defects. In the case of n-MCz, the neutrons introduce mainly p-type defects while charged particles mainly n-type defects. This effect was measured by capacitance-voltage measurements on diodes irradiated with one or the other type of radiation. This particular feature of the n-MCz silicon can though have a favourable consequence on the degradation rate of the electrical properties of the detectors when the damage is due to a comparable mix of neutron and charged hadrons because the n and p-type radiation induced defects can partially compensate. To test this effect, n-in-p FZ and n-in-n MCz detectors have been irradiated with neutrons only, and n-in-n FZ and n-in-n MCz detectors with an equal mix (5×10^{14} n_{eq} cm^{-2}) of neutrons and 26MeV/c protons, for a total dose of 1×10^{15} n_{eq} cm^{-2} for every sensor. Figure 6 shows the CC(V) measurements of these devices and confirms the compensation effect. The two FZ detectors exhibit almost identical CC(V) characteristics after both the neutron and mixed irradiation, while the n-MCz shows a faster rise of the CC(V) in the case of mixed irradiation.

5. Conclusions

Small microstrip detectors have been used to study the CC(V) properties of n and p-type FZ and MCz substrates readout with both n and p-side geometries. The detectors have been irradiated in three facilities with neutrons and protons of different energies. The comparison of the performances of similar detectors irradiated to equivalent fluences of 26MeV and 24GeV/c protons shows good agreement between the two irradiation sources.

The CC(V) measurements after both neutron and proton irradiations clearly confirm that the n-side readout yields a considerable advantage in term of signal detection. N-in-p detectors deliver a signal of bout 8000 electrons at 1000V bias even after neutron irradiations as high as 1×10^{16} n_{eq} cm^{-2}, while p-in-n devices provide a comparable or smaller signal after a ten times lower dose.

The comparison of the different substrates has clearly shown the superior performances of the n-MCz substrate after neutron irradiations up to 1×10^{15} n_{eq} cm^{-2}.

A mixed irradiation experiment has also been carried out. N-MCz and n and p-FZ detectors have been irradiated to a total dose of 1×10^{15} n_{eq} cm^{-2} with neutrons only or to 5×10^{14} n_{eq} cm^{-2} with neutrons followed by an equal dose of 26MeV protons. The n-MCz irradiated with both particles shows better CC(V) with respect to the FZ sensors and also with respect to the identical detector irradiated with neutrons only. This confirms the idea that charged hadrons and neutrons introduce defects that act as opposite signed doping in n-MCz silicon, which partially compensate in a mixed irradiation field, resulting in a slower degradation rate of the CC(V) at low bias voltages, at least to the measured dose of 1×10^{15} n_{eq} cm^{-2}.

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