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Charge multiplication in highly irradiated planar silicon sensors

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The discovery of the novel effect that amplifies the charge generated by ionising particles in heavily irradiates silicon detectors has risen hopes for further extending the lifetime of this type of sensors when exposed to heavy doses of hadron irradiation. The anomalous size (compared to expectations) of the signal generated by a minimum ionising particle (mip) in detectors irradiated to doses about one order of magnitude higher than what anticipated for the current Large Hadron Collider (LHC) at CERN has been reported for a number of years. It is now well documented that the correct interpretation for the improvement of the charge collection resides in the multiplication of the signal charge by impact ionisation. This effect is being intensively studied within the high energy physics detector community by mean of both experiments and simulations. The results of these studies are particular relevant to the silicon detectors planned for the future super LHC (sLHC) and for every silicon sensor that will be intended for very hostile environment, where the final cumulated flux will reach level of a few times 10^{16} 1MeV neutron equivalent (n_{eq}) cm^{-2}. A summary of the current results and the understood implications and limitations of this effect are here discussed.

Introduction

A considerable R&D activity for improving the radiation tolerance of finely segmented silicon detectors has been stimulated by the requirements of the future upgrade of the LHC accelerator at CERN. The silicon sensors that will certainly be used for the tracker and vertex sub-detectors in the upgraded experiments will suffer unprecedented radiation damage [1] having to withstand doses up to $\sim 2\times 10^{16}$ n_{eq} cm^{-2}. The extrapolation to sLHC levels of the performance of this type of sensors from their response to lower doses (for which a large number of data has been produced during the development of the sensors for the current LHC) would predict a signal too small for efficient operation of the tracking devices. Nonetheless direct measurements of the charge collection efficiency of microstrip detectors made with n-side readout on p-type silicon (n-in-p) have shown already at the early stages of this R&D that a relatively large signal was produced after heavy hadron irradiation [2] proving that this type of silicon devices could indeed survive even the sLHC doses. The accumulation in more recent years of charge collection measurements from heavily irradiated silicon detectors has confirmed the larger than expected signal (see e.g. [3-9]). In particular, a number of results have been produced within the framework of the CERN-RD50 collaboration, dedicated to the development of radiation hard detectors for future super-collider applications [10]. It has been shown that irradiated sensors were capable to recover at least the same charge as before irradiation, or even more if biased to sufficiently high voltages. The concept of charge multiplication as the only possible explanation for these unexpected results emerged and experiments and simulation tools have been set-up to investigate this mechanism.

Estimated signal after irradiation and discrepancy with measurements

The reduction of the signal with irradiation is usually ascribed to two effects:

i) The increase of the full depletion voltage with irradiation (see e.g. [11] for a summary)

ii) The increased effect of charge trapping [12].

The increase of the full depletion voltage has been documented in literature mainly using the capacitance-voltage characteristic to measure its value. Nonetheless, after high doses of hadron irradiation the concept of full depletion voltage loses most of its meaning and it is not a useful parameter for describing the performances of the silicon detectors [13]. The relevant parameter is in fact the amount of collected charge as a function of the bias voltage (CC(V)) which is affected by the increase of the charge trapping due to the radiation induced trapping centres that partially remove charge carriers from the signal current. The density of traps is assumed to increase linearly with fluence and the effective trapping time $\tau_{e,h}$ for electrons (e) and holes (h) changes like:

$$1/\tau_{e,h} = \beta_{e,h}\phi_{eq} \qquad (1)$$

where $\beta_{e,h}$ is the proportionality constant for electrons and holes. The ratio of the collection time of the signal (t_S) to $\tau_{e,h}$ defines the amount of charge loss to trapping according to:

$$Q_{signal} = Q_0 e^{-t_S / \tau_{e,h}} \qquad (2)$$

where Q_{signal} and Q_0 are the measured charge and the ionised charge in the active volume, respectively. $\beta_{e,h}$ depends on the type of irradiation. Measured value for β_e and β_h are about 3.7 and 5.7×10^{-16} cm^2 ns^{-1} for neutron irradiation for electrons and holes, respectively, and about 5.4 and 6.6×10^{-16} cm^2 ns^{-1} for charged hadron irradiation [12]. Equation 2 shows that shorter t_S yields a larger signal. A faster signal in segmented silicon sensors is achieved by collecting the electron current (faster than the hole current due to the three times higher mobility) and keeping the high electric field near the collecting electrodes. For this reason, it has been shown that segmented detectors read out from the n$^+$ implant (n-in-n or n-in-p geometries) provide noticeably higher charge collection than the more standard p-in-n after irradiation [13, 14].

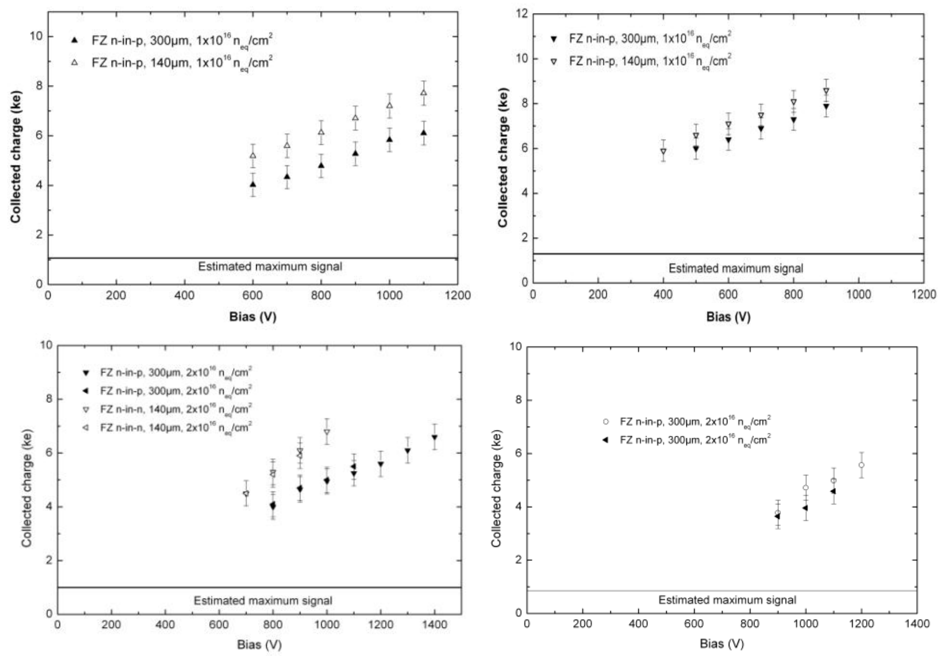

Figure 1: *Collected charge as a function of the bias voltage (CC(V)) of silicon microstrip detectors(140 and 300 μm thick)irradiated with 24GeV/c (top left), reactor neutrons(top right, bottom left)and 26MeV protons (bottom right, 300μm thick only)after 1and 2×10^{16} n_{eq} cm^{-2}. The figures also shows the expected maximum signal when the charge carrier trapping is considered [16].*

The detectors employed in high energy physics experiments need to be efficient in detecting minimum ionising particles (mip's) with an energy deposition in silicon of about 80 electrons μm^{-1}. Using the above parameterisation, and assuming that the charge trapping has the dominant effect on the reduction of the collected charge one can estimate the expected signal after a given dose. In particular, it is simple to give a value for the maximum expected charge, just assuming that all the carriers generated by the ionising radiation drift at the saturation velocity and using the carrier lifetime calculated from Eq 1. Unless otherwise specified, the experimental measurements here shown refer to the most probable value of the charge induced by a mip in segmented detectors read out with LHC speed electronics (40 MHz clock speed, [15]). Figure 1 shows the comparison of the expected and measured signals as a function of the bias voltage for silicon microstrip sensors after 1 and 2×10^{-16} n_{eq} cm^{-2} [16]. The clear inconsistency between data and expectations needs to be explained either revisiting the parameterisation or by considering a new effect that becomes important with high radiation doses. A mechanism for suppressing the charge trapping could be proposed to explain the results. This should involve a fast, or field enhanced, de-trapping that could account for the recovery of the signal to the pre-irradiation value.

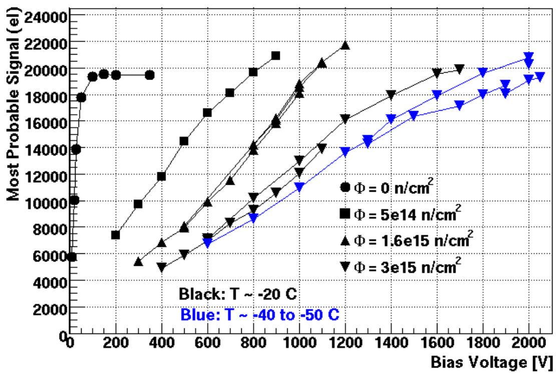

Figure 2: *CC(V) of neutron irradiated n-in-p microstrip detectors before irradiation and after various doses up to* 3×10^{15} n_{eq} cm^{-2}*. The charge measured by the pre-irradiated sensor is equalled or even slightly exceeded by the irradiated devices [4].*

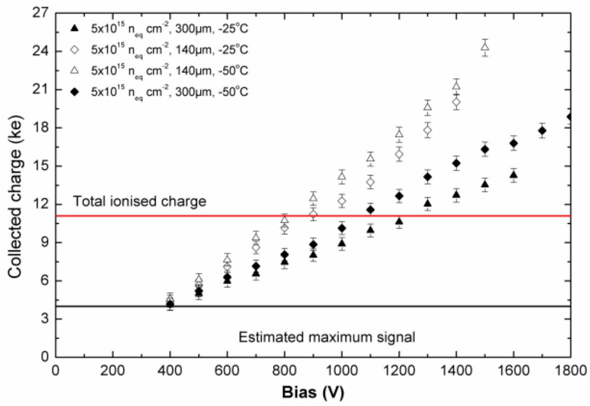

Figure 3: *CC(V) after irradiation with 26MeV protons of a 140 μm and a 300 μm thick sensors irradiated to* 5×10^{15} n_{eq} cm^{-2}*. The data have been collected at -25 and -50* ^{o}C*. The figure shows the expected maximum charge from trapping, and the charge measured by a non irradiated 140μm thick sensors. The charge measured by the irradiated 140μm thick sensors exceeds the ionised charge by a factor of about two (data from [16]).*

A signal equal to pre-irradiation values was indeed measured with sensors irradiated up to 3×10^{15} n_{eq} cm^{-2} thanks to the ability of irradiated sensor to stand very high voltages without breakdown as shown in Fig. 2 [4]. The bias voltage on this 300 μm thick devices could be as high as 2000 V, suggesting that the recovery of full charge collection only depends on the ability to provide a strong enough electric field to the sensor. Even so, only a complete suppression of the charge trapping at high bias voltages could account for the recovery of full charge collection efficiency. But a clear indication that the effect that allows these unexpected charge collection is not the suppression of the charge trapping is shown in Figure 3 [16]: here the signal measured by 140μm thick n-in-p microstrip sensors (readout with the similar type of electronics as above) exceeds the signal of the 300μm thick sensor with the same strip geometry and also corresponds to more than twice the signal measured by a non-irradiated device of identical thickness. The only possible explanation of the behaviour is the onset of a high electric field region where the signal charge is multiplied by mean of impact ionisation.

Further evidence with different geometries

The results shown above have been obtained with similar detectors, designed for the research activity in the CERN-RD50 collaboration and irradiated with different particles (24 GeV/c protons [17], reactor neutrons [18] and 26MeV protons [19]). They have 128 n-strip with 75µm pitch and ~ 1 cm length implanted on p-type bulk and have been produced by Micron Semiconductor UK(1) with 140µm and 300µm thick high resistivity Floating Zone (FZ) substrates. Results obtained with similar devices manufactured by a single supplier have to be proven for different geometries and vendors. The onset of charge multiplication could depend on geometry and manufacturing parameters (e.g. the junction profile implant, size of the electrodes, thickness of the device…) trough their possible impact on the shape of the electric field. It is important to investigate if the effect appears also with geometries different from the one above. In fact, the first published results showing high signal after heavy irradiation [2] were obtained with almost identical detectors made by CNM-IMB(2). Figure 4 shows the collected charge as a function of the bias voltage (CC(V)) for small (1x1 cm^2) detectors with ~75 µm strip pitch made by HPK(3). The results are in line with the measurements shown above for 300µm thick detectors with enhanced signal when compared to expectations. More data are available with devices produced by this manufacturer, confirming the high signal after irradiation [7, 20, 21]. Although production details are not known, it can be assumed that some differences in the junction profile are present among the three different foundries here mentioned, but these do not significantly affect the performances of the irradiated devices.

Charge multiplication takes places in very different types of irradiated silicon detectors. Measurements performed with simple pad diodes made with another type of silicon crystal made by a relatively high resistivity epitaxial (Epi) layer grown on a low resistivity Czochralski (Cz) silicon wafer show the onset of impact ionisation after irradiation. The Epi layer act as the sensitive volume of the sensor while the Cz silicon constitute the ohmic contact. Pad diodes produced on wafers made by ITME (4) with 75, 100 and 150µm Epi layer thicknesses have been produced within the RD50 collaboration. They have been irradiated to high doses and characterised with alpha particles and laser photons with different wavelength and range in silicon [22]. The onset of charge multiplication in irradiated devices has been well proven. Figure 5 shows the ratio of the charge collected by diodes with the three different thicknesses of the Epi layer after 1×10^{16} n_{eq} cm^{-2} under illumination with a 670 nm laser, with evidence of signal much larger than the pre-irradiation value [22].

The results here summarised have all been obtained with sensors produced with a planar photolithographic process. It has been found that the charge multiplication also occurs in segmented detectors built by etching columnar p^+ and n^+ doped electrodes through the silicon bulk, usually called 3-D sensors [23].

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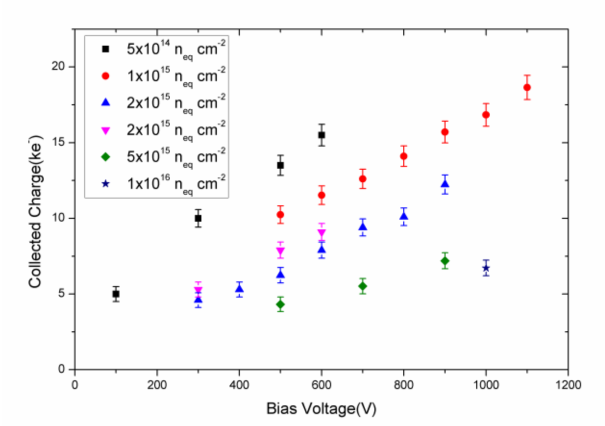

Figure 4: *CC(V) of neutron irradiated n-in-p microstrip detectors made by HPK(Japan) after various doses up to* 1×10^{16} n_{eq} cm^{-2}*. As for the micron detectors the charge collected by these 300µm thick sensors exceeds the expectations from the charge trapping. Data from [20] and [21].*

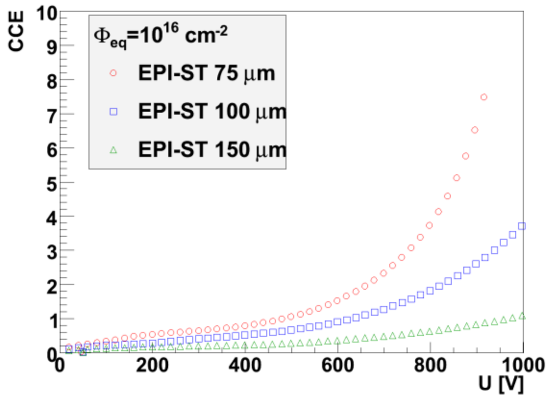

Figure 5: *Charge collection efficiency (CCE), normalised to the pre-irradiation charge, of epitaxial silicon pad diodes irradiated with 24 GeV/c protons [22] to* 1×10^{16} n_{eq} cm^{-2}*. The thicknesses of the epitaxial active layers of the three detectors shown are 75, 100 and 150 µm. The CCE at corresponding bias voltages is higher for thinner epitaxial layers.*

Effect of thickness on the charge multiplication

Figures 1, 3 and 5 show that the charge collection efficiency of severely irradiated detectors, both microstrips and pad diodes, is higher at corresponding bias voltages for thinner devices with otherwise identical electrode geometry and implant and bulk properties. The electric field for a given bias voltage is higher for thin devices and this explains the earlier onset of charge multiplication. The thickness could be an important parameter to operate heavily irradiated vertex detectors at lower bias voltages retaining full efficiency. This also meets the need for lower mass detector layers to minimise the multiple scattering at the inner radii of future experiments to improve the vertex resolution.

Besides the thickness of the detector, the size of the amplified signal (relative to the total ionised charge) depends on where the ionisation is created by the passing radiation. Figure 6 [22] shows the CCE of a 75µm thick epitaxial diode irradiated to 1×10^{16} n_{eq} cm^{-2} and illuminated with a pulsed red laser (670nm), an infrared laser (1060 nm) and by 5.8 MeV α particles from a ^{231}Am source. The penetration depth of these three types of radiation in silicon is about 3 µm, through the whole thickness and 28 µm respectively. Shallower ionisation results in higher charge multiplication because a larger fraction of the ionised charge is injected in or very close to the high field region, under the junction, where the impact ionisation takes place. It is assumed that the charge multiplication factor (M) is a property of the detector through its electric field profile and therefore independent on the ionisation depth. This is an implicit proof that the charge trapping is still effective in reducing the signal because the far charge carriers only contribute for a fraction of the total to the multiplied signal.

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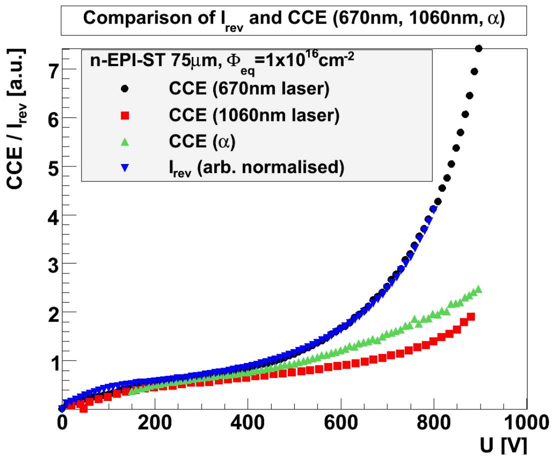

Figure 6: *Normalised CCE (with signal induced by α particles, 670 and 1060 nm lasers) and arbitrarily rescaled reverse current for pad detector irradiated with 24 GeV/c protons [22] to 1×10^{16} n_{eq} cm^{-2}. The shape of the current overlaps very well with the CCE curve for the shallower penetration ionising photons.*

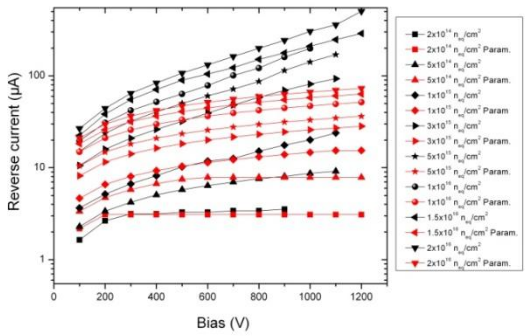

Figure 7: *Expected (red) and measured reverse current as a function of the reverse bias voltage (I-V) for silicon detector irradiated to different doses [24].*

Reverse current and noise

The impact ionisation also affects the reverse current, not only the charge carrier ionised by a passing particle. The shape of the reverse current characteristic versus the bias voltage reflects the effect of the impact ionisation, with an over-linear rise with increasing voltage. This characteristic does not correspond to the expected behaviour of the thermally generated reverse current in the semiconductor bulk, as it has been shown in [24]. This also means that the possibility of predicting the current after irradiation cannot rely on the accepted parameterisation valid at lower doses [11]. This parameterisation implies a reverse current proportional to the depleted volume and increasing linearly with the hadron fluence, which is clearly not verified by measurements on heavily irradiated sensors (Figure 7, [24]). A higher current has an impact on the detector power dissipation and on the noise. In particular, the noise in non-multiplying silicon detector systems equipped with modern amplifier ASICs can be expressed in term of equivalent noise charge (ENC, in electrons) as [15]:

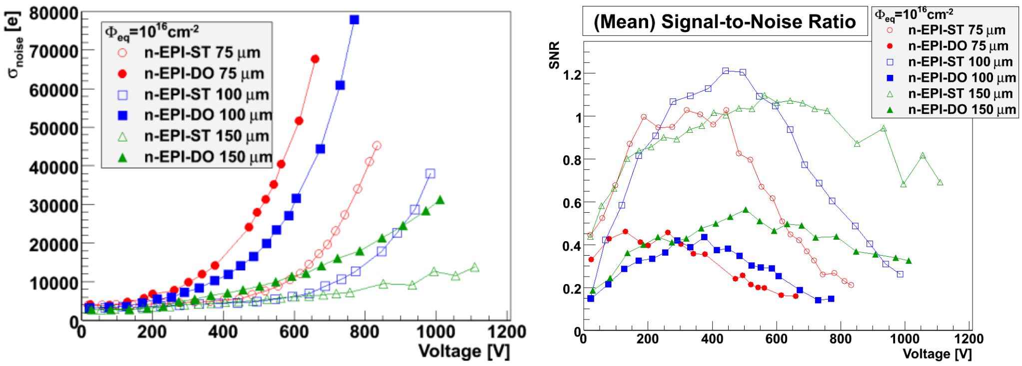

Figure 8. *Noise (left) and signal to noise ratio(right) as a function of the applied bias voltage for epi-diodes after* $10^{16} n_{eq}\ cm^{-2}$ *[26].*

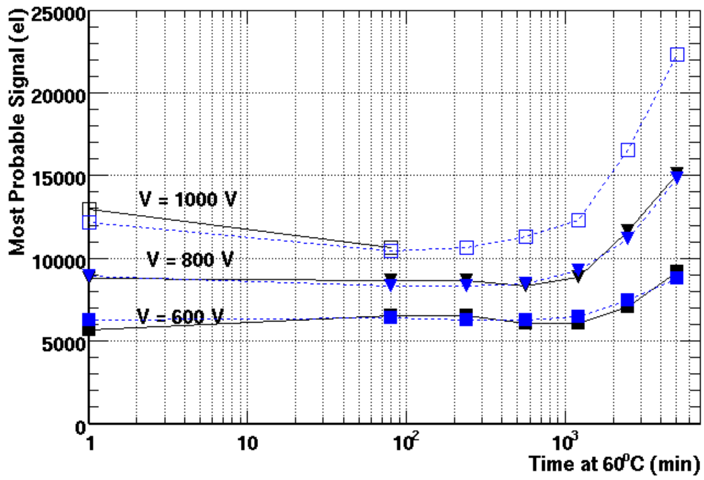

Figure 9: *Signal as a function of the annealing time at 60°C for a microstrip detector irradiated with reactor neutrons [29] to* $5\times10^{15}\ n_{eq}\ cm^{-2}$*. A strong increase of the signal, due to enhancement of the charge multiplication, is found towards the end of the annealing time here explored.*

$$ENC = \sqrt{(ENC_{serial} + ENC_{shot})} = \sqrt{(a + b\cdot C)^2 + (B\cdot I_R \cdot \tau_s)^2} \qquad (3)$$

where the second contribution (shot noise) is proportional to the reverse current I_R (expressed in nA) multiplied by the shaping time τ_S expressed in ns. The constant terms a, b anc B, appearing in Eq. 3 are characteristic of the particular amplifier ASIC, with the input capacitance C expressed in pF. When charge multiplication takes place the noise is higher than the value predicted by the Eq. 3 just with the increased I_R value. The accrued noise can be better quantified by:

$$ENC'_{shot}\left(M'\right) = M' \cdot \sqrt{F} \cdot ENC_{shot} \qquad (4)$$

where the expected shot noise contribution is increased by the multiplication factor M' and also by statistical fluctuation of the multiplied current that can contribute an excess noise factor F [25]. The multiplication factor of the current (M') and of the signal charge (M) could be different.

Figure 8 [26] shows the noise and the signal over noise ratio measured with pad diodes when multiplication takes place, with a significant increase of the noise with higher values of M and M'. The signal over noise ratio (which is an important figure of merit for any detector system) does not monotonically improve with the bias voltage, but exhibits degradation at higher values of the multiplication factor.

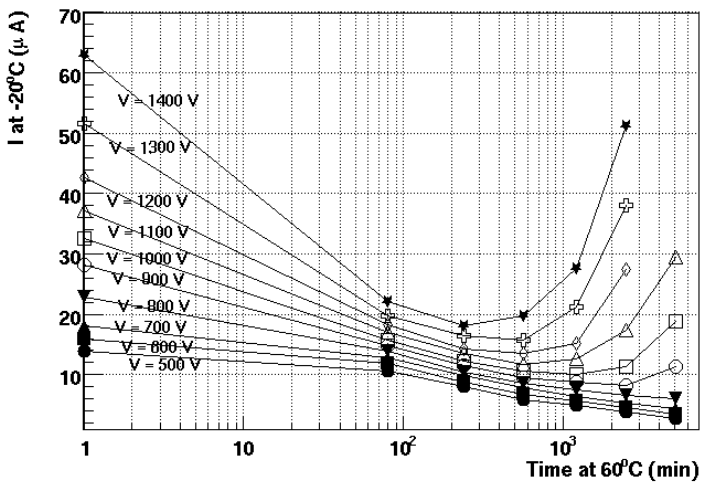

Figure 10: *Reverse current at different bias voltages for a microstrip detector irradiated with reactor neutrons [28] to* 5×10^{15} n_{eq} cm^{-2}*. At bias voltages of 900V and above, the current exhibits an increase after a certain annealing time. The time at which the current is higher with respect to the previous measurement at the same voltage is shorter for high voltage values.*

Annealing of CC(V) and reverse current

It has been shown that the annealing of the CC(V) does not follow that of the full depletion voltage (see e.g. [24] and references therein) even considering the effect of the annealing of the charge trapping probability that is reducing with time after irradiation [27]. The signal shows a significant increase for a few months (at 20°C) after irradiation and remains higher than the initial signal after irradiation for a few years. An important part in these behaviours is now known to be due to charge multiplication. The early measurements have been taken with the sensors biased to voltages where stable performances and negligible increase of the noise where found. If measurements are performed at the highest voltages achievable, the effect of the annealing on the charge multiplication becomes more evident [28]. Figure 9 shows an example of these results: the most probable value of the energy distribution of mip's crossing the sensor irradiated to 5×10^{15} n_{eq} cm^{-2} is found to increase significantly after 10^3 minutes at 60°C at every applied bias voltage. The increase can be explained only by an enhanced charge multiplication. In fact, the changes of the effective space charge with time (see e.g. [11]) would predict a thinner sensitive volume of the annealed sensor due to the reduction of the resistivity (and therefore higher V_{fd}) with fluence. The corresponding beneficial annealing of τ_{tr} is not sufficient to justify the increase of the signal. The accrued charge multiplication must be due to the changes of the effective space charge that take place with annealing due to the change of the chemical nature of the radiation induced defects. These changes must produce a stronger electric field in the proximity of the collecting electrodes with a resulting enhanced impact ionisation.

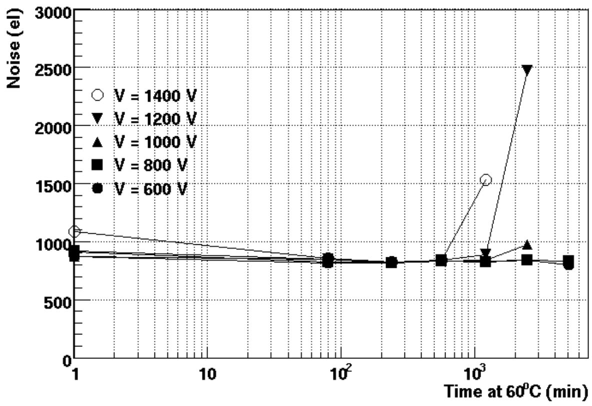

Figure 11: *Noise of a n-in-p detector irradiated to 5x10*^{15} n_{eq} *cm*$^{-2}$ *at different bias voltages as a function of the annealing time (at 60°C) measured with 40MHz clock speed electronics [28].*

It was also thought that the reverse current is indefinitely decreasing with annealing (see e.g.[11] and references therein). Also in the case of the reverse current the charge multiplication plays a major role that changes the annealing behaviour of severely irradiated sensors. Figure 10 shows the trend of the reverse current at different voltages as a function of time at 60°C [28]. A significant decrease is measured for 10^3 minutes (with the possible exception for the data at 800V). At the lower voltages the trend continues while at high ones the impact ionisation increases the reverse current enough to cause an inversion of the annealing trend. Interestingly, the noise is different for similar value of the current depending on the annealing history. In Fig. 10 it can be noticed that similar values of current are measured at different annealing stages at the same bias voltage. If the total noise was to be evaluated from Eq. 3 it should be identical irrespectively of the annealing time. Figure 11 shows instead that higher values of noise are induced when stronger multiplication takes place. The noise was measured with the same electronics and sensor with the same reverse current but at different stages of annealing. It is noticeably higher when the signal is larger, therefore with higher values of M (M') at longer annealing times, according to Eq.2. Besides, the extra noise due to the effect and the statistical fluctuations of the impact ionisation appears also with an increased rate of fake hits (microdischarge).

Simulations

In order to give an accurate quantitative description of the charge multiplication behaviour of irradiated silicon detectors, a precise knowledge of the electrical activity of the crystal defects (that introduce energy levels in the silicon band-gap) created by the radiation and changing during the annealing must be found and used to calculate the electric field profile in the silicon detectors. This complete knowledge is not yet available, despite a consistent effort dedicated to directly measure (with various spectroscopic and luminescence techniques [29]) the electrical characteristic and densities of the radiation induced traps before and after different annealing times. The favoured approach for attempting to compute the electrical properties of the irradiated silicon is the use of numerical methods for solving the Poisson and current continuity equations with updated modelling of the radiation damage (expressed in term of density and energy levels of defects in the silicon crystal band-gap). The effect of the radiation damage are usually introduced in the simulations referring to the findings of the microscopic measurements and using *effective* defects artificially envisaged to reproduce the macroscopic electrical measurements (mainly reverse current and full depletion voltage at different temperatures). Although the irradiation models used for simulations have achieved good performance, they are not yet capable of accurately reproducing all the measured features of irradiated devices. In particular, the charge multiplication in irradiated silicon sensors is a rather novel experimental result and the simulations are just starting ([30-32]) to model and reproduce this effect. Significant results have already been obtained to confirm the impact ionisation as the effect responsible for the enhanced signal, although the numerical precision of the simulated signals and currents need to be improved. Figures 12 and 13 show some example of these results. The first figure shows the comparison of the charge collection efficiency between 140 and 300 μm thick sensors before irradiation and after 1×10^{16} n_{eq} cm^{-2} [30]. As seen in the measured data, charge multiplication is found that is larger, at the same bias voltage for the thin device.

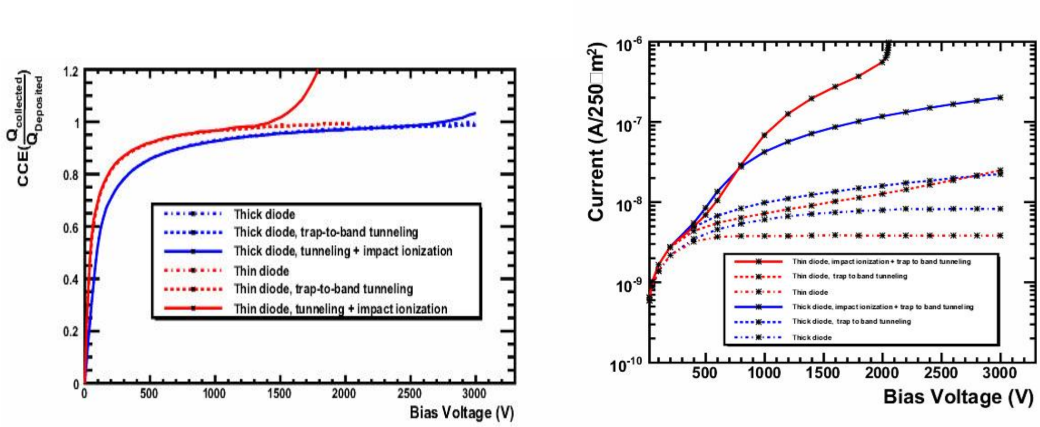

Figure 12*: Example of simulation that qualitatively reproduces the charge multiplication effect in diodes of different thicknesses (140 and 300 μm) irradiated to $1x10^{16}$ n_{eq} cm^{-2}.The multiplication effect appears only when the impact ionisation model is switched on in the simulation [30].*

The simulation of the irradiated sensors can reproduce the multiplication effect on the charge collection when the simulation program uses the inter-defect transient and the impact ionisation model. Figure 13 [31] shows a similar trend (a charge enhancement is computed at bias voltages above 700 V for a sensor irradiated to 1×10^{16} n_{eq} cm^{-2} using the Overstraeten model [33] for impact ionisation). The figure also reports measured data with a detector with the same characteristics of the simulation. It can be seen that the quantitative agreement is still poor, requiring further work to adjust the simulations by improving the knowledge of the electric field profile and possibly tune the impact ionisation model.

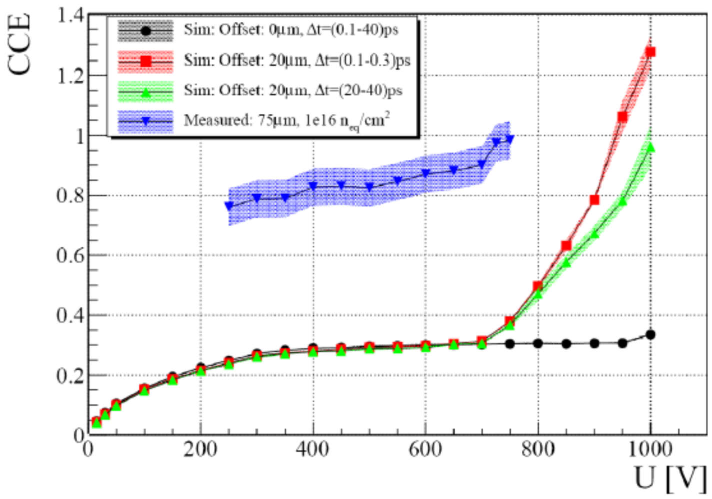

Figure 13: *Comparison of simulated and measured charge collection efficiency of a thin (75 µm) detector irradiated to 1x10*^{16} n_{eq} *cm*$^{-2}$*. The multiplication effect is here reproduced at high bias voltages, but the simulation is still far from describing the measured data points [31].*

The large amount of data available through the research activity within RD50 both in term of microscopic investigation of the radiation induced defects and measurements of the performance of irradiated detectors with different geometries is expected to feed into the simulation activity to lead to the understanding of the charge multiplication effect that is essential for reliable prediction of the performance of sensors that will cover large areas in experiments where long time exploitation (and large irradiation doses) without possibility of intervention is anticipated.

Conclusions

The charge multiplication is a property of irradiated silicon detectors that has the potential for extending their lifetime in future super-colliders applications for high energy physics, or in any application where severe hadron irradiation is expected. It has been found that the increase of the signal is associated with an increase of the reverse current and noise. This latter also shows an excess factor that in many situations can offset the advantages of the charge multiplication. Probably low values of M (M') are required to retain the advantages of an enhanced signal while keeping a large signal to noise ratio and negligible false hits counts. At present the thickness of the detectors and the applied bias voltage seem to be the parameters for tuning the charge multiplication to optimise the signal over noise ratio. Nonetheless other possibilities for optimising the multiplication could be found in the fine adjustment of the junction profile or of the electrode geometry. Further experimental studies with varied junction profiles and electrode shapes, and the improvement of the simulation tool should lead to the understanding of the charge multiplication mechanism and allow its confident exploitation for silicon detectors exposed to severe radiation environment.

Acknowledgement

The research here presented was performed within the framework of the RD50 collaboration. This collaboration is dedicating a particular effort to further study the charge multiplication mechanism in heavily irradiated silicon detectors.

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