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Degradation of charge sharing after neutron irradiation in strip silicon detectors with different geometries

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ABSTRACT

The aim of the CERN/RD50 collaboration is the improvement of the radiation tolerance of semiconductor detectors for future experiments at high-luminosity colliders. In the RD50 framework, evidence of enhanced signal charge in severely irradiated silicon detectors (diodes, segmented planar and 3D devices) was found. The underlying mechanism was labelled charge multiplication. This has been one of the most exciting results from the research activity of RD50 because it could allow for a greatly extended radiation tolerance, if the mechanism is to be found controllable and tuneable. The charge multiplication mechanism is governed by impact ionisation from electrons drifting in high electric field. The electric field profile is influenced by the geometry of the implanted electrodes. In order to investigate the influence of the diode implantation geometry on charge multiplication, the RD50 collaboration has commissioned the production of miniature microstrip silicon sensors with various choices of strip pitch and strip width over pitch (w/p) ratios. Moreover, some of the sensors were produced interleaving readout strips with dummy intermediate ones in order to modify the electric field profile. These geometrical solutions can influence both charge multiplication and charge sharing between adjacent strips. The initial results of this study are here presented.

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1. Introduction

The results shown at the 14th RD50 workshop [1] have provided the final evidence for enhanced charge collection (already suggested by previous measurements (e.g. [2,4])) in irradiated silicon sensors. The mechanism has been labelled with the name of charge multiplication and it is most likely due to impact ionisation from hot electrons transported in the strong electric field in proximity of the junction that is present in heavily irradiated sensors. Extended radiation tolerance for silicon sensors would be possible if technologies can be developed for controlling and tuning this mechanism. A possible way to influence the electric field profile near the junction of segmented silicon detectors is to vary the geometry of the implanted electrodes.

2. Silicon microstrip detectors with various strip geometries

A dedicated photolithography mask set for processing micro-strip sensors has been designed within the RD50 collaboration to explore several variations of the strip pitch and strip width over pitch ratio. Besides, some sensors with intermediate strips of

different types have been introduced in this mask set. Intermediate strips have been proposed for improving the resolution of AC coupled micro-strip detectors while keeping a reduced number of readout channels [5]. The sensors geometry was n-type readout strips implanted on high resistivity (14 kOhm cm) p-bulk, so the signal is mainly due to the electron current. This geometry is the optimal choice for radiation hardness [2–4] and for investigating charge multiplication, which is only expected from the electron current. To this purpose, the intermediate strips are implanted structures similar to the readout ones, therefore connected to the common bias rail with a 1–1.5 MOhm resistor, but not provided with an AC coupled metal layer for readout connection. They are interposed to the readout strips. A significant improvement of the hit resolution is achieved due to the enhanced charge sharing introduced by the intermediate strips. A reduction is expected in the measured total cluster charge due to losses to the intermediate strips. For this reason, this solution is not implemented in detectors deployed in high radiation environments where a severe reduction of the signal is already caused by the radiation damage to the silicon crystal. In the RD50 charge multiplication (CM) mask, nonetheless, we wanted to study the effect of intermediate and floating intermediate strips, these last ones with no connection to the bias rail. This floating implant would not remove charge from the cluster signal, but it can influence the electric field in the strip

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Table 1

Main geometry variations available on the RD50-CM mask. The detector names reflect the different geometries: P# is the strip pitch in micrometer, W# is the strip implant width in micrometer, I# is the width of the intermediate strip (when present) in micrometer, F# is the width of the intermediate floating strip (when present) in micrometer.

Name	Strip pitch (μm)	Strip width (μm)	Intermediate biased strip (μm)	Intermediate floating strip (μm)
P40-W6	40	6	No	No
P40-W15	40	15	No	No
P40-W27	40	27	No	No
P40-W15-I6	40	15	6	No
P40-W15-F6	40	15	No	6
P40-W15-F15	40	15	No	15
P40-W15-I15	40	15	15	No
P80-W6	80	6	No	No
P80-W60	80	60	No	No
P80-W25-F10	80	25	No	10
P80-W25-I10	80	25	10	No
P80-W25-F35	80	25	No	35
P80-W25-I35	80	25	35	No
P100-W10	100	10	No	No
P100-W33	100	33	No	No
P100-W70	100	70	No	No
P100-W33-I15	100	33	15	No
P100-W33-F15	100	33	No	15
P100-W33-F33	100	33	No	33
P100-W33-I33	100	33	33	No

Fig. 1. Charge collected (MPV) as a function of the bias voltage (CC(V)) with various geometry (see Table 1) sensors irradiated with neutrons to $5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$.

region. Table 1 shows the various types of $1 \times 1 \text{ cm}^2$ sensors, with 128 readout strips, implemented in the RD50-CM mask set.

Also the thickness of the sensors has an impact on charge multiplication, because a stronger electric field is expected in thinner sensors biased to the same voltage ([6,7]). For this reason, n-in-p sensors 150 and 300 μm thick have been produced by Micron Semiconductor Ltd. [8] with the mask set described above.

3. Irradiation and characterisation

A set of sensors from 150 and 300 μm thick wafers has been irradiated in the Triga Mark II research reactor of the JSI in Ljubljana [9] to $5 \times 10^{15} \text{ 1 MeV neutron equivalent (n}_{\text{eq}})$ [10] cm^{-2} . The sensors have been characterised after irradiation without any further annealing than the one associated with the necessary handling of the sensors at room temperature, estimated in a total of 12 h at 20 °C. The sensors have been kept always at temperatures between $-15 \text{ }^\circ\text{C}$ to $-25 \text{ }^\circ\text{C}$ for storage and

measurement, preventing subsequent annealing [11] effects. The sensors were glued to an aluminium radiator and bonded to the readout electronics. The radiator has the function of stabilising the sensor temperature to the environment temperature during measurements. All measurements presented here were performed with the sensors glued to the radiator and the readout electronics put in a freezer kept at $-25 \text{ }^\circ\text{C}$. The microstrip detectors were characterised by the measurement of the most probable value (MPV) of the charge spectrum induced by beta electrons from a

Fig. 2. Charge collected (MPV) as a function of the bias voltage (CC(V)) with various geometry (see Table 1) 150 and 300 μm thick sensors irradiated with neutrons to $5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. Open symbols, 150 μm thick sensors, full symbols, 300 μm thick.

Fig. 3. Charge collected (MPV) as a function of the bias voltage (CC(V)) with various geometry (see Table 1) 300 μm thick sensors irradiated with neutrons to $5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. Full symbols no intermediate strips; open symbols intermediate floating strips; grey symbols intermediate strips. Although there is no clear separation, the sensors with intermediate biased strips exhibit a smaller collected charge than sensors with floating or no intermediate strips as anticipated in section 1. There is also indication that wider intermediate strips have a bigger impact on reducing the signal charge. These results can be explained in terms of larger fraction of charge lost to the wider intermediate strip. On the other hand, the intermediate floating strips do not cause a reduction of the collected signal: Fig. 3 seems to point to a small improvement with respect to the standard geometry, but more measurements with other devices and after different radiation fluences are needed to prove this possible enhancement. Another important parameter for segmented silicon sensors is the resolution. This is known to degrade with irradiation, because of the decreased charge sharing with fluence that causes an increased number of one strip clusters (therefore loosing the improved resolution achieved by charge division). It is expected that the intermediate strips influence the charge sharing. Fig. 4 shows the comparison of the percentage of one, two and three strip clusters as a function of the bias voltage for detectors with 40 μm pitch, 15 μm strip width, without and with intermediate strips (biased and floating). The effect of the biased intermediate strips on the cluster size is evident, while the intermediate floating strips only exhibit a very small enhancement of two strip cluster with respect to the standard geometry sensor.

Fig. 4. Percentage of one, two and three strip cluster as a function of the bias voltage for 40 μm pitch, 15 μm strip width, without and with intermediate strips (biased and floating) irradiated to $5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ (top to bottom, respectively).

^{90}Sr radioactive source as a function of the bias voltage. The source is located above the device under test and the trigger is provided by a scintillator below the sensors. A 2 mm plastic absorber is placed on top of the scintillator to remove the lower energy electrons from the ^{90}Sr beta emission spectrum. In this way, the selected higher energy electrons have an MPV close to the typical value of minimum ionising particles (mip, typically with an MPV of about 24000 electrons in 300 μm of silicon [12]). The readout was performed with the Alibava system [13], based on the 40 MHz clocked Beetle ASIC (128 channels analogue strip readout).

4. Results after irradiation

The results of the MPV measurements of all the sensors irradiated to $5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ are reported in Fig. 1. The plot shows a large dispersion of values for the same applied bias voltage, indicating significantly different performance from sensors with different geometries.

Some of this difference is due to the thickness. It has already been found that after heavy irradiation thinner sensors produce a higher signal, at the same applied bias voltage, than 300 μm thick sensors [6,7,14]. Fig. 2 shows the MPV as a function of bias voltage for thin and standard sensors of different geometry (in term of strip pitch and width) but with no intermediate strips.

At the same applied bias voltage, thinner sensors generate higher signal charge, in agreement with previous results. It should be noted that the maximum collected value is about 11000 electrons, very close to the maximum expected signal (the pre-irradiation value of the MPV for the thin devices is about 12000 electrons).

To assess the influence of other geometrical parameters on the collected signal charge, the analysis should compare the MPV for

detectors with the same thickness. Fig. 3 shows the results obtained with the 300 μm thick sensors.

5. Conclusions

The RD50 sensors c effect of the junction implant size and of the use of intermediate structures on charge collection after severe hadron irradiation. Sensors with various geometries irradiated with reactor neutrons to $5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ have shown enhanced MPV as a function of the bias voltage in thinner devices. They also show that, as expected, the use of intermediate strips enhances the charge sharing but has a negative effect on the total collected charge after irradiation. If the intermediate strip is floating, it does not reduce the charge collection with respect to standard devices. These latter sensors exhibit a small improvement of collected charge and charge sharing relative to standard devices (with no intermediate strips) but further data with more detector types irradiated at different fluences are needed to prove the extent of this possible enhancement.

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