Charge collection and charge sharing in heavily irradiated n-side read-out silicon microstrip detectors

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Elsevier use only: Received date here; revised date here; accepted date here

Abstract

Hadron radiation damage of n-bulk silicon detectors leads to a change in the effective space charge from positive (n-type) to negative (p-type). This effect is called type inversion. Type inversion occurs after exposure to a fluence of a few 10^{13} protons cm^{-2} and is characterized by migration of the diode junction to the n^+ implanted side (n-side) of the detector. After inversion the charge collection efficiency (CCE) of segmented detectors at low voltage is higher when the n-side, rather than the p-side, is read out. A p-side read out (p-in-n) and an n-side read out (n-in-n) strip detector with identical strip geometry and a wafer thickness of 200 µm were simultaneously and inhomogenously irradiated to a maximum fluence of 7×10^{14} protons cm^{-2} with 24 GeV/c protons. A comparison of the charge collection efficiency at very high irradiation doses is shown with these two read out geometries.
The inhomogeneous irradiation induces an inhomogenous distribution of the effective space charge with a transverse component of the electric field that could in principle affect the resolution properties of the microstrip detector. The inter-strip charge sharing properties, as a function of dose, for the n-in-n detector have been measured. No systematic distortion of the reconstructed cluster position was detected within the limits of the measurement accuracy. The detectors were manufactured using oxygen enriched silicon substrates to limit the degradation of the full depletion voltage under charged hadron irradiation. The measured charge collection efficiency confirms that the use of oxygenated n-in-n detectors is viable up to fluences of 7×10^{14} protons cm^{-2}.

Silicon microstrip detectors, radiation hardness, charge collection.

1. Introduction

Experiments performing CP violation studies in the b-quark sector require accurate secondary vertex reconstruction. Highly segmented silicon microstrip detectors are an option for the vertex detectors in these experiments. At the LHC two general purpose detectors (ATLAS, CMS) will be equipped with pixel and microstrip sensors. A third LHC experiment, LHCb, is exclusively dedicated to the study of b-physics. The LHCb spectrometer will possess a specialized vertex locator (VELO) comprised of silicon microstrip detectors positioned very close to the interaction point (<1 cm). They will therefore be exposed to very high hadron fluxes up to 1.3 10^{14} cm^{-2} neutron equivalent per year. As the VELO detectors will be positioned in a vertical plane, relative to the beam axis, they will receive an inhomogeneous dose (the hadron flux in the LHCb VELO is predicted to be approximately proportional to $1/R^2$, where R is the radial distance to the beam). An inhomogeneous effective space charge (N_{eff}) profile across the sensor will be generated by the irradiation; this will induce a transverse electric field that can shift the charge collected at the read-out strips and may systematically distort the reconstructed positions of charge clusters in the device. The inhomogeneous irradiation should not affect the general functionality of microstrip silicon detectors, as it has been shown by tests performed for the Vertex Detector System of HERA-b (see e.g. [1]).

LHCb-VELO prototypes have been designed by the University of Liverpool and fabricated by Micron Semiconductor [2]. To enhance the radiation hardness to charged hadrons, the sensors were manufactured on oxygen enriched silicon substrates [3,4]. All data presented in this article were taken using these LHCb VELO sensors.

2. Irradiation of the prototype detectors

Two 200 µm thick (one n-in-n and one p-in-n) detectors were irradiated in the CERN-PS IRRAD [5] irradiation facility with 24 GeV/c protons. The detectors were all VELO Phi-measuring sensors [6,7], which are segmented with quasi-radial strips, designed to measure the azimuthal angle of tracks from the interaction.

The beam spot in the IRRAD facility is ~2.5×2 cm^{-2} in the vertical and horizontal direction respectively. The detectors were positioned with the detector plane parallel to the beam, and with the beam centre offset by ~1 cm from the detector centre. The detectors were irradiated simultaneously to the same fluence. The irradiation profile across the individual detectors was highly inhomogeneous, ranging from non-irradiated areas ($<3 \times 10^{13}$ p/cm^{-2}) to a maximum of 7×10^{14} p cm^{-2}. Figure 1 shows the irradiation profile as measured with aluminium foil activation technique [8].

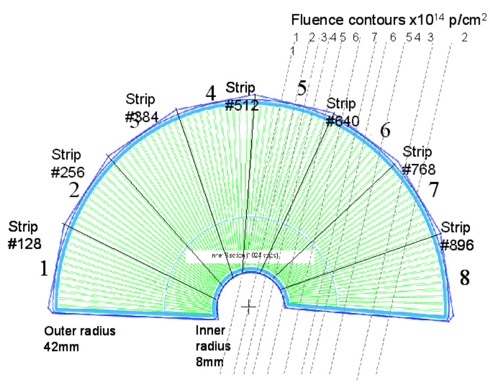

Fig. 1. Contour of the 24 GeV/c fluence as measured with Al foils activation method.

3. Experimental results

The irradiated sensors were studied in the laboratory using a collimated ^{106}Ru β-source and a 1060 nm wavelength laser terminated with a focuser from OZ Optics [9]. The size of the light spot was ~6µm FWHM at the focal length of 1.2 cm. The spot size was given by the manufacturer and confirmed by the measurement of the metal strip width. The laser spot was focused close to a metal strip and moved across the strip in 2 µm steps. The aluminium strip screens the signal. The scan over the metal strips allows the evaluation of the size of the light spot and the determination of the centre of the metal strip with good accuracy (~1 µm). Moreover, the symmetry of the signal on either side of the metal strip is an

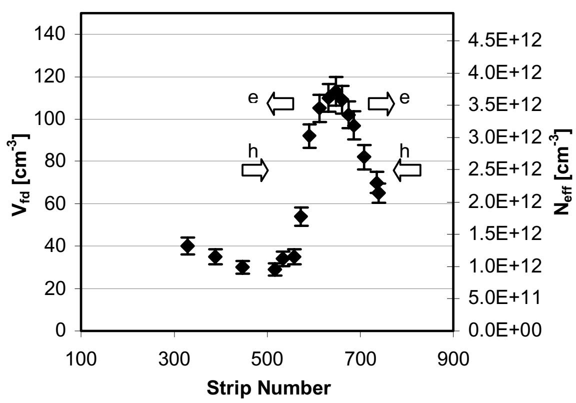

Fig. 2. Full depletion voltage (V_{fd}) and effective space charge ($|N_{eff}|$) profile across the detector, as evaluated by fitting the CCE(V) curves. measured on the outer end of the outer strips. The profile matches the spatial irradiation profile. (Note Channels 580 to 800 span about 25mm). Also shown are the directions of systematic displacement of holes and electrons due to non-uniform irradiations, in the two different areas of high $|N_{eff}|$ gradient

indication of the perpendicularity of the light beam and the detector plane. The output power of the laser was tuned to give a signal of approximately 4 times the signal from the β-particles. The sensors were read out at the front-end using SCT128a analogue LHC speed ASICS [10] operating at 40MHz. The ASIC data were acquired, when using the laser, with a wide bandwidth scope (LeCroyLC574AC). When using the β-source the data were digitised using a high speed ADC (LEPSi 40MHz Sirocco) and a custom built data acquisition system.

The detectors were mounted on the plate of an "x-y" stage that allowed the sensors to be moved with a precision of 1 μm in two dimensions perpendicular to the injected laser light.

The charge collection efficiency as a function of voltage, CCE(V), was studied using the laser over the differently irradiated regions of the detector. Different strips have received a different hadron fluence, as shown in Fig. 1. The CCE(V) was measured by focusing the laser light spot next to the various strips in the outer area of the detector. The

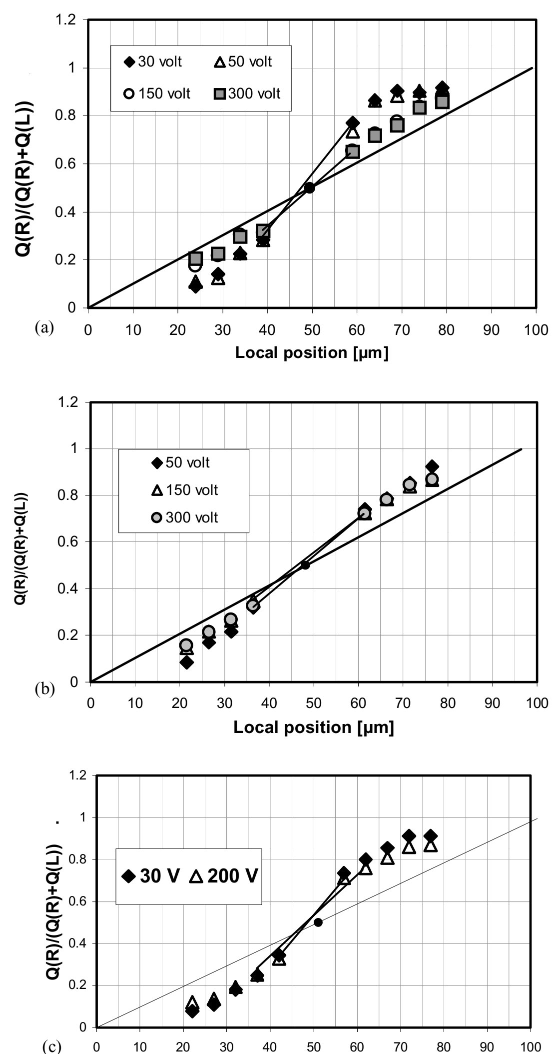

Fig. 3. η curve measured between strips located in regions with (a) low V_{fd} and low gradient of N_{eff}, (strip # 517-518) (b) high V_{fd} and high positive gradient of N_{eff} (strip # 590-591) and (c) high V_{fd} and high negative gradient of N_{eff} (strip # 670-671).

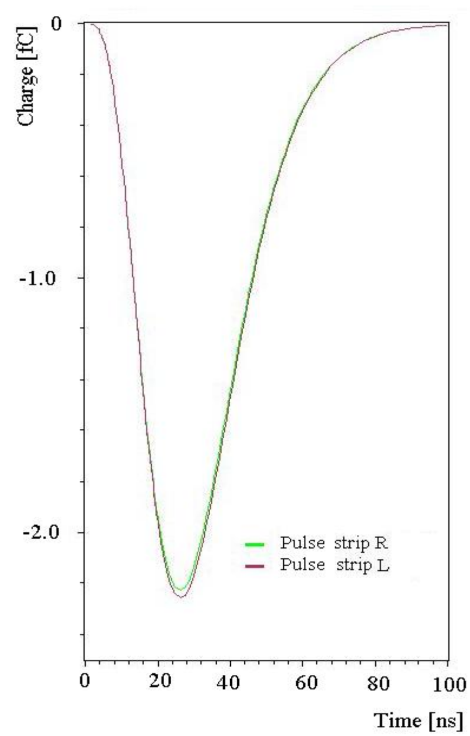

Fig. 4. ISE TCAD simulation of the pulse shape of strip L and R when a minimum ionising particle impinges in the midpoint between two strips and perpendicularly to the surface. The signal of the detector is convoluted with the shaping function of the SCT128a chip. The simulated gradient of N_{eff} between the strips corresponds to the highest of the n-in-n detectors. The difference in the pulse height of strip L and R corresponds to a shift of the impinging point of about 1 micron towards strip L

full depletion voltage, V_{fd}, was evaluated by fitting the CCE(V) curves [11]. The resulting profile of V_{fd} (and therefore of the effective space charge density, N_{eff}, proportional to V_{fd}) is shown in Fig. 2. The shape corresponds the inhomogeneous irradiation profile and exhibits two areas with a strong gradient ($\sim 1 \times 10^{13}$ cm^{-4}) but with opposite sign. In the high gradient regions we expect a component of the electric field parallel to the detector plane and perpendicular to the strips of the order of 500 V cm^{-1}, compared to a vertical component of ~ 20 kV cm^{-1}. These transverse components will move the charge carriers generated by the ionising radiation and influence the reconstructed cluster position. The shift will depend on the sign of the gradient of N_{eff} and the reconstructed cluster positions in the detector should be affected accordingly.

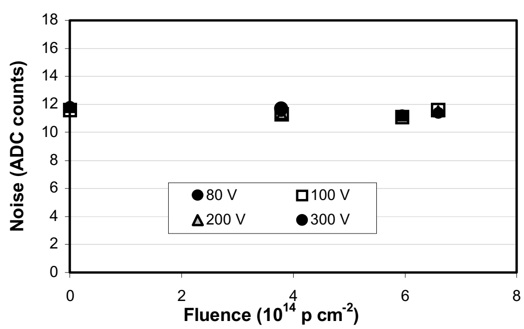

Fig. 5: Noise as a function of fluence measured with the SCT128A analogue LHC speed electronics.

To study this effect, the charge division between two adjacent strips (left (L) and right (R)) has been measured in different areas of the detector. The charge division has been evaluated using the charge collected on the two strips when the centre of the laser spot was located at a distance *x* from the centre of strip L. The ratio (η) of charge seen by strip R to the total charge is defined as follows:

$$\eta(x) = Q_R / (Q_R + Q_L) \qquad (1)$$

where Q_R and Q_L is the charge collected by strip R and L respectively. Figures 3(a)(b) and (c) show the η distribution measured between strips located in regions with low V_{fd} and low gradient of N_{eff}, high V_{fd} and high positive gradient of N_{eff} and high V_{fd} and high negative gradient of N_{eff}, respectively. The mid point of the three distributions coincides with the mid-point between the strips to within ~2 microns, suggesting that the shift induced by the transverse component of the electric field is smaller than this upper limit.

The pulse shape of strip L and R for a minimum ionising particle impinging on the midpoint between two strips and perpendicularly to the surface has been simulated using ISE TCAD [12] and convoluted with the shaping function of the SCT128a chip. Fig. 4 shows the result of the simulation. The simulated gradient of N_{eff} between the two strips corresponds to the highest gradient of the irradiated detectors. The difference in the pulse height of strip L and R

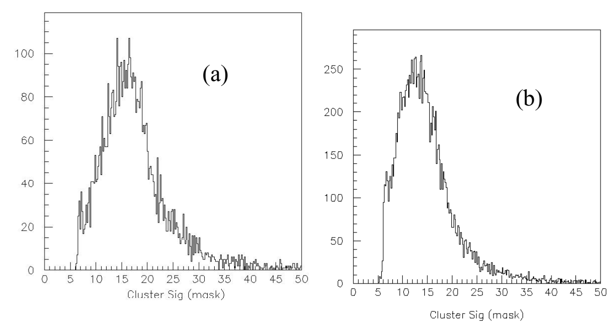

Figure 6: Cluster significance in (a) a non-irradiated area and (b) in an area irradiated to 7 10^{14} p cm^{-2}.

corresponds to a shift of the point of incidence of about 1 micron towards strip L. This is in agreement with the upper limit found experimentally.

The inhomogeneous irradiation of the detector also provides the unique opportunity to study the charge deficit induced by the trapping of the charge carriers at radiation induced trap centres and hence to evaluate the signal to noise ratio (S/N) as a function of the fluence on the same device. To study the S/N a highly collimated β-source was used in preference to the laser. A 3mm thick absorber was used to select high-energy electrons that release a comparable energy to a minimum ionising particle (MIP). The FWHM of the hit distribution of the electrons spanned over ~ 20strips. In this study only the centre 5-10 strips were used to evaluate the charge collection properties in an area with defined radiation damage. Moving the detector under the source allowed measurement of the differently irradiated areas of the detector. The noise measured with LHC speed electronics is dominated by the contribution of the input capacitance. This capacitance (~7 pF for the n-in-n detector) does not change with irradiation and the detector contribution to the total noise is independent on the fluence, when measured with LHC speed electronics, as shown in Fig. 5. Fig. 6 shows the signal and the cluster significance in a non-irradiated area and in an area irradiated to 7 10^{14} p cm^{-2}. Figure 7 shows the signal to noise ratio measured in the n-in-n detectors as a function of the received dose. The degradation of the signal after the highest fluence is 78%, which indicates that the detector is still fully operational.

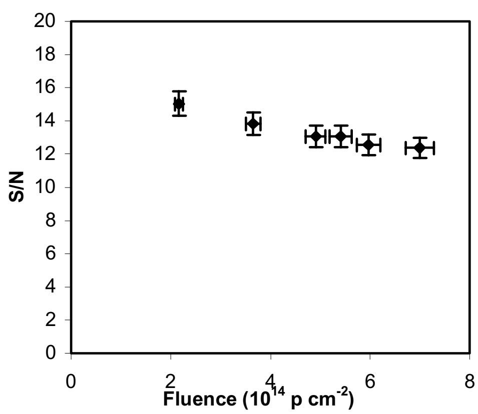

Fig. 7. Signal to noise ratio (S/N) as a function of proton fluence measured in the differently irradiated areas of the n-in-n detector.

This value was achieved at a bias voltage of 400 V. The charge collection curves in n-in-n detectors reach the plateau value at lower voltages compared to p-in-n, as shown in Fig. 8.

4. Conclusions

The inhomogeneous irradiation of the LHCb VELO prototype detectors allowed to study the charge collection properties of n-in-n and p-in-n devices up to very high fluences and the charge sharing properties with a high gradient of the effective space charge across the detector and perpendicular to the strip.

The possible shift in the resolution resulting by this gradient has been studied and no distortion of the η curves has been detected within the errors of ~ 2 μm.

The use of n-side read-out on oxygen enriched silicon substrates yields tracking detectors good to 7 10^{14} p cm^{-2} with 78% charge collection efficiency. A charge collection efficiency higher than 60% can be predicted for an oxygenated n-in-n detector after 1 10^{15} p cm^{-2} biased at 500 volts, making these detectors operational also after such a high charged hadron dose.

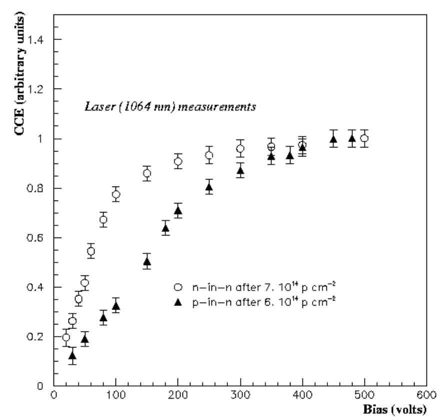

Fig. 8 Comparison of charge collection as a function of the applied bias voltage in heavily irradiated n-in-n and p-in-n detectors.

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