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Evidence of enhanced signal response at high bias voltages in planar silicon detectors irradiated up to 2.2×10^{16} n_{eq} cm^{-2}

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ABSTRACT

The signal generated by minimum ionising particles in segmented planar silicon sensors irradiated to hadron fluences exceeding 2×10^{16} n_{eq} cm^{-2} has been measured with 40 MHz clock speed analogue electronics. The results show a surprisingly high signal after these doses, well above the maximum expected charge predicted by the trapping of charge carriers at radiation induced defect centres. The ability of irradiated sensors to withstand high bias voltages allows for the collection of a substantial signal that is sometimes higher than the signal measured before irradiation.

1. Introduction

The upgrade of three of the main experiments (ATLAS, CMS and LHCb) hosted in the present large hadron collider (LHC) and the future super-LHC (sLHC) will require tracker and vertex detectors capable to operate after doses of hadron irradiation up to 2×10^{16} 1 MeV neutron equivalent (n_{eq}) cm^{-2} [1–3]. Segmented silicon sensors are the strongest candidate for these detector systems, due to their speed, resolution and low mass. Nonetheless, the highest required dose is so severe that the ability to use silicon sensors fabricated with the standard planar technology is questioned. The key point is to prove that they can collect a sufficient amount of charge to provide a signal over noise (S/N) ratio capable of fully efficient tracking after the highest dose. The study of the signal induced by minimum ionising particles (mip's) in silicon microstrip sensors produced in planar technology is here presented before and after various hadron irradiation fluences up to 2×10^{16} n_{eq} cm^{-2}.

2. Expected signal in irradiated silicon sensors

Silicon segmented sensors made in planar technology have been successfully used for tracking in high energy physics experiments for a few decades [4,5]. The most used readout geometry in the past and present experiments is p^+ implanted strips on n-type high resistivity bulk (p-in-n), due to the simpler and cheaper processing with respect to n-side readout (n^+ segmented implants on n- or p-type high resistivity crystal). The thickness of the bulk could be down to 300 μm, which can be considered the present standard for silicon detectors in high energy physics applications. Studies targeted on improving the radiation tolerance of the sensors have though proved that n-side readout of segmented silicon detectors (n-in-p or n-in-n) results in a much enhanced radiation hardness with respect to the more standard p-side readout (see e.g. [6–8]). For this reason, and due to the cheaper and simpler processing than that of n-in-n, the currently favoured choice for radiation hard microstrip sensors is the n-in-p geometry. Although with a reduced rate with respect to the p-in-n devices, the signal of n-side readout sensors deteriorates with hadron irradiation as shown in Fig. 1 for proton and neutron irradiation.

Two effects concur to this degradation: the increase of the full depletion voltage (V_{FD}) and the charge trapping. Both effects are due to radiation induced defect centres with energy levels within the bandgap of the crystalline silicon [9,10]. These defects also cause the increase of the reverse current (I_R) as a function of fluence. The increase of the V_{FD} reduces the active (depleted) volume of the silicon sensor for a given bias voltage. Only the ionised charge deposited in the active volume escapes recombination and contributes to the signal current. The charge generated by a minimum ionising particle (mip) is proportional to the path length of the particle in the sensitive volume of the silicon detector. A reduction of the active volume corresponds to an equivalent diminution of the signal. The square of the depth d of the active volume is proportional to the bias voltage V_B through the effective space charge density (N_{eff}):

$$V_B = \frac{ed^2 |N_{eff}|}{2\varepsilon_0 \varepsilon_{Si}} \tag{1}$$

where e is the electron charge and $\varepsilon_o \varepsilon_{Si}$ is the permittivity of silicon. When $V_B = V_{FD}$, the depleted depth of the sensor corresponds to its thickness w. The depletion depth of the sensor

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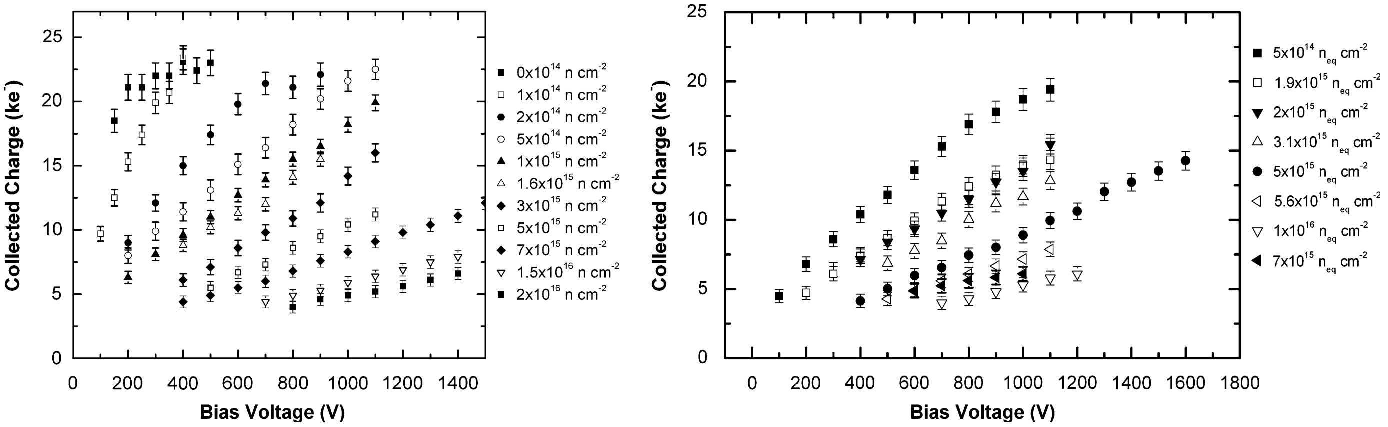

Fig. 1. Charge collection as a function of the reverse bias voltage (CC(V)) of standard (300 μm thick) microstrip detectors irradiated to various doses of reactor neutrons (left) and 26 MeV and 24 GeV/*c* protons (right).

for a given $V_B < V_{FD}$ is therefore,

$$d(<w) = \sqrt{\frac{V_B}{V_{FD}}}w. \tag{2}$$

Eq. (2) also provides the method for measuring the full depletion voltage. The capacitance of a silicon detector is inversely proportional to the thickness of the depleted volume. The variation of the capacitance as a function of the applied reverse bias (the CV curve) saturates at the detector thickness, when the value of the bias is V_{FD}. The changes of N_{eff} with hadron fluence have been extensively studied and can be parameterised with the following expression:

$$N_{eff}(\phi) = N_D e^{-c\phi} - N_A e^{-d\phi} + \beta\phi \tag{3}$$

where N_D is the initial donor concentration, N_A is the initial acceptor concentration, *c* and *d* are the removal constants and β is the parameter accounting for the net introduction of acceptor-like defects. At high doses, the first term of Eq. (3) can be neglected, and the dependence of N_{eff} (V_{FD}) on the fluence is linear. The value of β depends on the silicon crystal and the type of irradiation (charge and energy of the radiation) [10,11]. A value often accepted in literature, for oxygen enriched, high resistivity floating zone silicon is $\beta = 0.028\ \text{cm}^{-1}$ [12].

After heavy doses, the reduction of the active volume becomes severe. The value of V_{FD} estimated using Eqs. (1) and (3) and the above value of β is about 2000, 20,000 and 40,000 V after 1, 10 and $20 \times 10^{15}\ \text{n}_{eq}\ \text{cm}^{-2}$, respectively, for 300 μm thick sensors. Using these values, the active volume of a silicon detector irradiated to these three fluences is ~200, <70 and <50 μm for 1000 V bias. The ionised charge in the active volume is equal to ~16,000, 5000 and 3500 electrons, respectively. The direct measurements of V_{FD} that lead to the parameterisation reported in Eq. (1) have been performed only up to about $1 \times 10^{15}\ \text{n}_{eq}\ \text{cm}^{-2}$ with standard thickness sensors (300 μm). It is possible that the assumption of a linear degradation of N_{eff} at high fluence is not correct. With thinner detectors, the changes of N_{eff} can be measured after higher doses, due to the lower applied bias voltage required to deplete the detector (Eq. (2)). Fig. 2 shows the changes of N_{eff} (V_{FD}) as a function of the irradiation fluence, measured using 140 μm thick silicon diodes irradiated with reactor neutrons at the Triga Mack II research reactor of the JSI of Ljubljana [13]. The measurements have been performed with devices irradiated up to $1.5 \times 10^{16}\ \text{n}_{eq}\ \text{cm}^{-2}$. V_{FD} was estimated using the CV method. The thinner detectors have a V_{FD} about 5.6 times lower than that of the standard 300 μm ones (Eq. (1)). This allows the use of the CV method to study the changes of N_{eff} as a function of fluence to much higher doses. The change of N_{eff} with dose is compatible with Eq. (3) and the above value of β up to $1 \times 10^{15}\ \text{n}_{eq}\ \text{cm}^{-2}$, but it is considerably reduced at higher fluences. Table 1 shows the expected depletion depth of a silicon detector after different irradiation doses and the amount of ionised charge in the active volume in the case of linear dependence of N_{eff} with fluence (Eq. (3)), or according to the measurements of Fig. 2.

The charge trapping is the second factor that contributes to the reduction of the signal as a function of hadron fluence. The charge trapping centres introduced by the radiation are capable of holding the signal charge carriers, effectively removing them from the signal current. The density of the traps is assumed to increase linearly with fluence, causing a considerable reduction of the average signal carrier lifetime. This can be described by the following expression:

$$\frac{1}{\tau_{e,h}} = \beta_{e,h}\phi \tag{4}$$

where $\tau_{e,h}$ is the effective trapping time for electrons (*e*) and holes (*h*), $\beta_{e,h}$ is the proportionality constant for electrons and holes and ϕ is the 1 MeV n_{eq} fluence. The ratio of the collection time ($t_{ce,h}$) of the signal to $\tau_{e,h}$ defines the amount of charge loss to trapping according to

$$Q_{signal} = Q_0 e^{t_{ce,h}/\tau_{e,h}} \tag{5}$$

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 values for β_e and β_h are about 3.7 and $5.7 \times 10^{-16}\ \text{cm}^2\ \text{ns}^{-1}$ for 1 MeV neutron irradiation for electrons and holes, respectively, and about 5.4 and $6.6 \times 10^{-16}\ \text{cm}^2\ \text{ns}^{-1}$ for charged hadron irradiation [14]. The effective trapping times also define the charge collection distance (CC_D) in irradiated silicon. Assuming that the electric field is high enough to drift all the charge carriers at saturation velocity towards the collecting electrode, the product of the saturation velocity times $\tau_{e,h}$ provides the CC_D after the relevant fluence of charged or neutral hadron irradiation. In the case of n-side readout, the signal is dominated by the electron current and one can neglect the hole contribution. Table 1 shows the estimated CC_D and expected signals in n-side readout segmented detectors for neutron doses from 5×10^{15} to $2 \times 10^{16}\ \text{n}_{eq}\ \text{cm}^{-2}$. In the case of charged hadron irradiation, an even stronger reduction of the CC_D is expected. It appears that the charge trapping is causing more severe signal degradation than the increase of V_{FD} with fluence. The β_e and β_h constants have been directly measured only up to about 1×10^{15} $\text{n}_{eq}\ \text{cm}^{-2}$, because over-depletion of the sensor is needed for this measurement. It is therefore possible that after higher doses the