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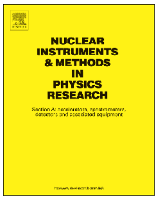

Signal formation in irradiated silicon detectors

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ABSTRACT

In this paper we present an initial study on the effects induced by radiation on the signal generated by a minimum ionising particle in silicon detector. The results are obtained by implementing in the simulation programme Weightfield2 (WF2) charge carrier trapping and non linear distribution of the electric field. Results of sample simulations are presented, along with a discussion of the limitations of the current approach and ideas for future improvements.

1. Introduction

Radiation damage in silicon detectors results into three main changes of the detector performance: (i) a variation of the effective doping concentration and distribution, (ii) an increase in the leakage current, and (iii) a decrease in the charge collection efficiency. These effects are the measurable consequences of the creation of defects in the silicon lattice, which act as either sources or sinks of charge carriers. The defects created are assumed to scale linearly with the amount of energy deposited into displacements, and the damage created by any kind of particle has been related to that of a 1 MeV neutron trough the use of a hardness factor. Nevertheless, defect generation is still considerably particle dependent. While any impact particle having a sufficiently high energy to create a primary knock-on atom leads to the creation of simple point defects, neutral hadron irradiation is also largely responsible for the production of cluster type defects. Such microscopic differences have a large impact on the macroscopic properties mentioned at the beginning of the section [1]. Many works have already proposed a parametrisation of the change in the detector's macroscopic properties in function of the fluence. The trapping induced decrease of signal has been modelled following an exponential fashion [2–4]:

$$I = I_0 e^{\frac{-t}{\tau_{eff}}} \qquad (1)$$

where τ_{eff} refers to the effective trapping time, which is inversely proportional to the fluence ϕ:

$$\frac{1}{\tau_{eff}} = \beta\phi \qquad (2)$$

The leakage current, on the other hand, has been observed to have a linear dependance on the fluence [5]:

$$I_{leak} = \alpha(t, T)V\phi \qquad (3)$$

with α being the leakage current damage constant, and V the volume of the detector. The evolution of the effective doping concentration has been found to be more complex. Not only donor and acceptor like defects are introduced changing the effective dopant concentration, but the dopant distribution itself evolves to be no longer uniform. The result is a change of the electric field from linear to quadratic, and the appearance of the so called double junction.

2. Weightfiled2

WF2 is a simulation programme aimed at describing the performance of silicon and diamond detectors [6]. A graphical user interface allows for the input of several parameters, like the configuration of the detector (number of strips, doping layers, thickness, width and pitch) and the working temperature and voltages (bias and depletion). These are then used as starting points to determine the detector's operational characteristics. After the electric field distribution is derived from the depletion voltage

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using Poisson's equation, the energy released by an incoming particle, whose type is selected by the user, is calculated with the aid of GEANT4 libraries. The induced signal current is then derived from Ramo's theorem. The drift of the electron-hole pairs generated by each incident particle (the choice of more than one MIP is possible, and the impact point and angle are customisable from the GUI) is followed, with a precision selected by the user (in terms both of percentage of electron-hole pairs simulated and of time unit) and a velocity calculated with respect to the drift field, mobility and saturation velocity. Amongst the doping configuration selection, the possibility of simulating a sensor with internal charge multiplication is present. The gain, chosen by the user from the GUI, has an exponential dependency on both a multiplication coefficient (determined by the local electric field giving rise to the multiplication) and the distance travelled along the electric field. The output of the simulation consists of several plots displaying the various components of both current (electrons, holes, and gain carriers) and electric field (Ex and Ey). An optional feature allows to simulate the response of both a broadband and a charge sensitive amplifier, and to visualise the oscilloscope's signal [6].

3. Implementation of radiation damage effects

To fully simulate the performance of an irradiated detector three factors should to be taken into account: (i) the change in the electric field from linear to quadratic, (ii) the generation of the additional charge carriers that constitute the leakage current, and (iii) the trapping of the charge carriers leading to the reduction in charge collection efficiency. As WF2's primary aim is to simulate the pure signal form, rather than including any kind of additional noise, it has been deemed appropriate to only include the changes concerning the electric field and the carrier lifetime, neglecting entirely the effects of the leakage current. Such changes have been addressed by introducing four free parameters (β_e, β_h, N_{eff} and N_A/N_D, whose significance will be explained in the following paragraph) in the graphical user interface, all of which can be adjusted to match experimental values and subsequently employed to make predictions. Seeing that WF2 individually follows the drift of each charge carrier, trapping has been implemented following a Monte Carlo-like treatment, extrapolating the probability for a single electron and hole to be trapped each nanosecond from the exponential current decay outlined in the introduction:

$$P_{trapping} = 1 - e^{-\beta\phi} \tag{4}$$

The value of the parameter β can be experimentally determined, and is usually found to differ between electrons and holes. The basis of the charge correction method for the determination of the effective trapping time lies in the assumption of an exponential decrease of charge with time. The integral of the induced current does not exhibit any saturation in an irradiated detector. It is in fact characterised by a rise at voltages above the full depletion voltage, where the higher electric field reduces the drift time, and thus the amount of trapped charge. The determination of the effective trapping time is achieved by correcting the measured induced currents with an exponential such that the charge obtained by integration of such induced currents is constant for all voltages above V_{depl}[2]. In the literature, several studies aimed at determining an accurate value of β can be found [2–4] highlighting a dependance of such parameter both on the irradiation type (neutral or charged hadrons), and on the detector type (doping type as well as manufacturing process). For this reason, the parameter β is left for the user to input (in units of 10^{16} cm^2 ns^{-1}). The basic idea would be to extrapolate the specific value from charge collection efficiency studies on the desired detector type, and use it to make predictions for different geometries and thicknesses, and for higher fluences. These predictions are expected to hold as long as two fundamental conditions are obeyed: a uniform distribution of the traps within the detector bulk (a condition which is expect to hold, as it is a fundamental assumption behind the entire treatment of trapping in this circumstance), and an independence of the parameter β on the fluence. As mentioned in the introduction, the evolution of the electric field due to radiation damage is complex as it involves both changes in dopant concentration and distribution, and does not follow any directly recognisable pattern. As a consequence, the present approach towards the matter consists in deriving the electric field from a dopant concentration and distribution entirely user selected. This is carried out by offering a choice between a linear and a step dopant distribution throughout the detector's bulk in the graphical user interface, with the number of additional dopant atoms N_{eff} (in units of 10^{12}) and the ratio between donors and acceptors N_A/N_D specified by the user. In this way it becomes possible to simulate various conformations of the field, and compare the signal from an alpha particle or from edge TCT with experimental data and extract the value of N_{eff} and N_A/N_D for a fluence and given detector type. While it is evident how the adopted strategy hardly provides any predictive power in terms of varying fluence or detector type, it nevertheless remains a valid tool for investigating the effects of a non linear electric field on a MIP signal. Once a higher amount of measurements has been performed, it could ideally be possible to determine N_{eff} and N_A/N_D β_e and β_h from comparison with experimental data for an array of fluences and detector types. A database could then be integrated in WF2, such that an accurate performance prediction would be obtained simply by specifying the type of the detector of interest and the amount of charged or neutral hadronic irradiation it is subject to. WF2 also offers the possibility of including acceptor creation by deep traps and initial acceptor removal [7]:

$$N_A(\Phi) = g_{eff}\Phi_{eq} + N_A(0)e^{-c_2\Phi_{eq}} \tag{5}$$

where $N_A(0)$ is the initial acceptor number, $g_{eff} = 0.02\,\text{cm}^{-1}$ and $c_2 = 4*10^{-9}N_A(0)^{-0.4}$ is a factor that depends on the initial acceptor concentration (assuming complete initial acceptor removal).

4. Simulation results and comparison to experimental data

On the basis of the description above, various simulations have been conducted to examine the changes in the performance of irradiated detectors with different thicknesses and gain values, and some of the results are hereby presented. Using the values β_e and β_h derived in [2] for n-in-p neutron irradiated FZ detectors, charge collection efficiency curves have been produced which highlight the advantages of the choice of thinner detectors and of the presence of an extra gain layer.

Although when scaled to the full multiplied charge collected prior to irradiation the degradation of the signal due to trapping appears visibly more pronounced in Low Gain Avalanche Detectors (LGAD) [8] (Fig. 1 left side), the signal yielded thanks to the presence of the extra gain layer still exceeds that of a conventional detector (Fig. 1 right side) for all investigated fluences. Such result is considerably more pronounced in thin detectors. The general reduction in signal is more than halved for a 50μm sensor compared to the common 300μm. Furthermore, the performance of thin LGADs suffers from a much less drastic reduction than thicker ones, which, for fluences of about $5{\cdot}10^{15}n_{eq}$ cm^{-2} seem to approach the efficiency of traditional devices.

Figs. 2 and 3 display the evolution of the signal typically

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