Modelling The Effect of Radiation Damage in Silicon Detectors

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Abstract

Within the topic of radiation damage on silicon detectors, a general description of the main effects of such phenomenon is provided, and a first implementation of fluence dependent trapping in the simulation program Weightfield2 is proposed, along with a discussion of the limitations of the current approach and ideas for future improvements.

1 Introduction

1.1 Radiation Effects on Silicon

Radiation damage in silicon detectors results into three main changes of the detector performance: (i) a variation of the effective doping concentration, (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.

When a particle traverses the silicon it can interact with one of the atoms and, if its energy exceeds 25 eV (the "displacement threshold energy")[1], this interaction can be non ionising, and displace the atom from its original position, leaving a vacancy behind and creating a so called "primary knock atom" (PKA). The PKA, in turn, migrates through the lattice, leading to the creation of point defects by further displacement, before it stops, creating an interstitial. The final result is, along with the original Frenkel pair, a track of point defects, and, in cases where the recoil energy of the PKA was sufficiently large (above 5 keV [2]), the presence of a dense agglomeration of defects, the so called "cluster", at the end of the track, where the cross section of elastic scattering, being inversely proportional to the velocity, is at a maximum [4]. This configuration is largely unstable due to the high mobility of vacancies and interstitials in Silicon above 150K, which leads to both a large recombination, and the generation of electrically active defects from the interactions of the interstitials between themselves and with the dopant atoms. These are the defects mainly responsible for the changes in the macroscopic detector properties.

Electrically active defects can be either donors, defined as neutral when occupied by an electron, or acceptors, which are positively charged when an electron is present. The occupancy of such defects at room temperature is dictated by the position of the energy level with respect to the Fermi level (E_F): states below it are occupied while for energies above E_F the electrons can escape to the conduction band. A further distinction is found between shallow and deep defects, the first being close to the band edges, and thus ionised at room temperature, the seconds close to the Fermi level, and electrically neutral. Deep defects acting as generation centres are responsible for the leakage current, while the trapping phenomena lowering the charge collection efficiency can be caused by any kind of defect, the most effective being the ones with a high capture cross section and detrapping time. The change in the effective doping concentration is a result of two processes: (i) dopant removal by formation of new complex defects between the original dopant and the newly created defects, and (ii) introduction of ionized defects that, even without being the same elements as the original dopants, act like them [4]. Depending on the type of irradiation, the phenomenon of dopant removal can become prominent to such an extent that the all the original donors/acceptors disappear (or, to be more precise, their effect on the charge carriers is completely cancelled), and the effective doping type of the detector is changed. In reality, this phenomenon is only observed in "n type" detectors (those doped with donor type defects), and can be traced back to the fact that irradiation seems to primarily generate acceptor type defects and favour the creation of vacancy-phosphorous complexes which deactivate the initial phosphorous doping [3].

The dopant distribution is responsible for the electric field present in the detector: ionised acceptors providing negative space charge, and ionised donors positive space charge. Irradiation modifies not only the dopant concentration, but also its spatial distribution, leading the originally linear electric field present in silicon pads to exhibit a so called "double junction" behaviour. This is believed to be the combined result of charge drift and trapping: leakage current electrons drift towards the anode while holes drift in the opposite direction, both getting constantly trapped and detrapped on the way, and leading to, for a simple model with constant drift velocity, a linear distribution of free and trapped carriers, and an associated quadratic electric field [5].

A useful variable to be introduced to quantify the amount of radiation impinging a detector is the fluence, generally defined as the number of particles incident on the surface of a sphere divided by the crossectional area of the sphere, and which in this context represents the number of particles per unit area that have irradiated the detector. As mentioned before, the collisions causing displacement damage in the lattice are the so called "non ionising" ones, and the associated energy deposition is named "non ionising energy loss", or NIEL. According to the NIEL scaling hypothesis, the defects created are assumed to scale linearly with the amount of such energy deposited into displacements, and the damage created by any kind of particle can be related to that of a 1 MeV neutron through the use of the so called "hardness factor". This provides an extremely useful tool for expressing any fluence in terms of "1 MeV neutron equivalent" per squared centimetre.

It's important to underline that the unification of the damage caused by different particles introduced by the NIEL scaling hypothesis doesn't imply a homogeneous reaction of the silicon to all kinds of irradiation: defect generation is in fact considerably particle dependent. Typically, the presence of cluster defects is associated with a neutral hadron irradiation, while point defects are believed to be generated by any impact particle having a sufficiently high energy to create a PKA. This suggests a difference in the effect of neutrons, scattering elastically on the atomic nuclei, and also causing nuclear reactions if sufficiently energetic, and charged particles, interacting primarily by ionisation, and causing displacement through Coulomb interaction (with a highly fractionated energy deposition). This difference has in fact been observed with regards to the properties mentioned at the beginning of the section [2] [4]. Although a slightly different trapping efficiency has also been noticed amongst the different radiation damages [6], the biggest discrepancy lies in the evolution of the effective doping concentration: in charged hadron irradiated n type detectors, not only the donor removal is less pronounced, but it stops before reaching type inversion, and the opposite trend is observed after the minimum in phosphorus concentration; neutron irradiation, on the other hand, shows a consistent acceptor introduction trend after the complete donor removal (and thus type inversion) [3]. For what concerns p type detectors, on the other hand, the two irradiation types seem to have a much similar result where the initial and not much pronounced acceptor removal is quickly followed by a large introduction of boron-like defects [11].

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 [6] [7] [8]:

$$I = I_0 e^{\frac{-t}{\tau_{eff}}} \tag{1}$$

where τ_eff refers to the effective trapping time, which is inversely proportional to the fluence ϕ:

$$\frac{1}{\tau_{eff}} = \beta\phi \tag{2}$$

The leakage current, on the other hand, has been observed to have a linear dependance on the fluence [9]:

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

with α being the leakage current damage constant, and V the volume of the detector. The evolution of the effective doping concentration is more complex, and characterised by two main trends: an initial dopant removal and a final and much more pronounces dopant introduction. This are quantified according to the Hamburg model [2]:

$$\begin{aligned} \delta N_{eff} =& N_A(\phi_{eq}, t(Ta)) + N_C(\phi_{eq}) \\ &+ N_Y(\phi_{eq}, t(Ta)) \end{aligned} \tag{4}$$

1.2 Weightfield2

Weightfield2 is a simulation program aimed at describing the performance of silicon and diamond detectors. [10].

A graphical user interface allows for the input of several parameters, amongst which the configuration of the detector (number of strips, doping layers, thickness, width and pitch) and the working temperature and voltages (bias and depletion), which are used as starting points to determine the detector's operational characteristics. After the electric field distribution is derived from the depletion voltage 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, and the induced signal current is derived from Ramo's theorem.

The electric field's calculations are performed iteratively by discretising the equation (derived by combining Poisson's and Laplace equation) on a grid, and the computation time is significantly reduced with the use of a multi grid structure in which the potential calculation is started on a coarser gird and then refined to one with halved mesh size at each iteration step. The x and y components of the electric and weighting field are calculated numerically for each point int the grid, and, in case the optional external magnetic field is present, the drift field is rotated by a Lorentz angle.

For every incident particle selected (the choice of more than one MIP is possible, and the impact point and angle are customisable from the GUI) the generated eh pairs are simulated, and their drift is followed, with a precision selected by the user (in terms both of percentage of eh 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, where 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), and an optional feature allows to simulate response of both a BroadBand and a Charge Sensitive amplifier, and to visualise the oscilloscope's signal. [10].

2 Method and Results

2.1 Present Status of Weightfield2

To fully simulate the performance of an irradiated detector three factors should to be kept in count: (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. In the following report this last point will be addressed.

Starting from the exponential current decay outlined in the introduction, it can be inferred that such behaviour also characterises the reduction in the number of charge carriers N, such that, given that usually the parameter β is expressed in cm^2/ns, the probability for a single carrier to be trapped each nanosecond corresponds to:

$$P_{trapping} = 1 - e^{-\beta\phi} \tag{5}$$

The value of β is experimentally determined by fitting the modelled exponential decay of charge

Table 1: Values of the proportionality constants determined by Kramberger et al. [6]

	ß(charged hadrons)[10ˆ-16 cmˆ2/ns])	ß(neutrons)[10ˆ-16 cmˆ2/ns]	K
electrons	5.7±0.2	4.1±0.1	-0.86±0.06
holes	7.7±0.2	6.0±0.2	-1.52±0.07

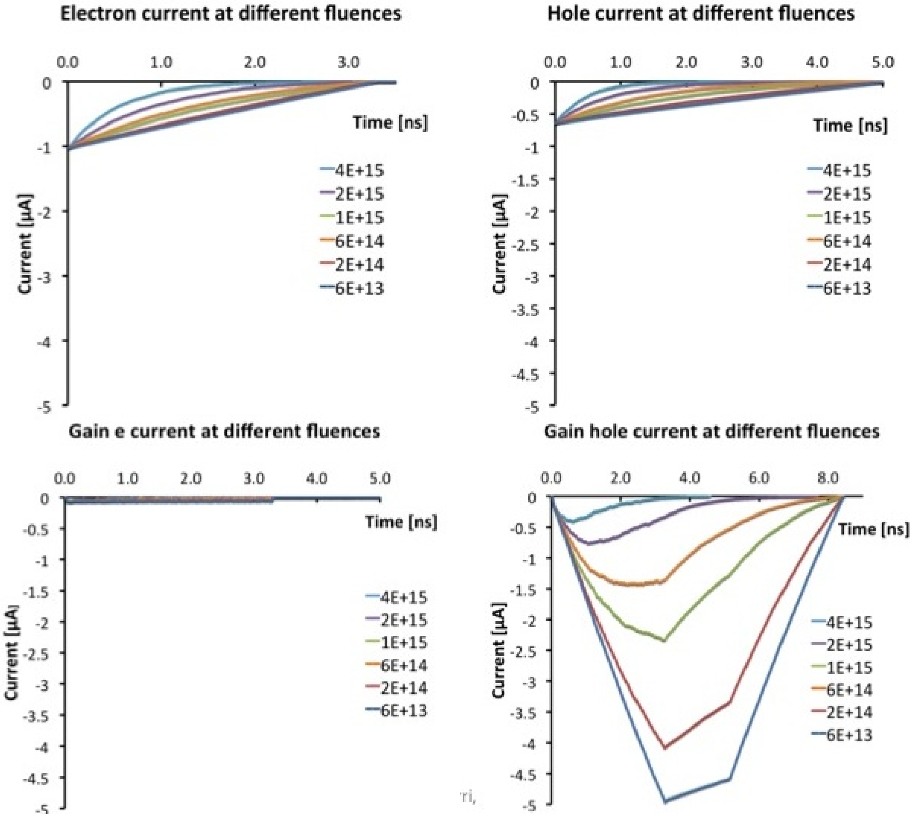

Figure 1: Variation of the different components (electron, holes, gain electrons, gain holes) of the current signal of an irradiated 300 μm silicon detector with fluence

collection efficiency with fluence to the data gathered via TCT measurements. 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, for which the integral of the induced current doesn't exhibit any saturation in an irradiated detector but is characterised by a rise at voltages above the full depletion voltage, where the amount of trapped charge decreases as a consequence of the higher electric field reducing the drift time. 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}. [6]

In the literature, several studies aimed at determining an accurate value of β can be found [6] [7] [8], sometimes in slight disagreement with

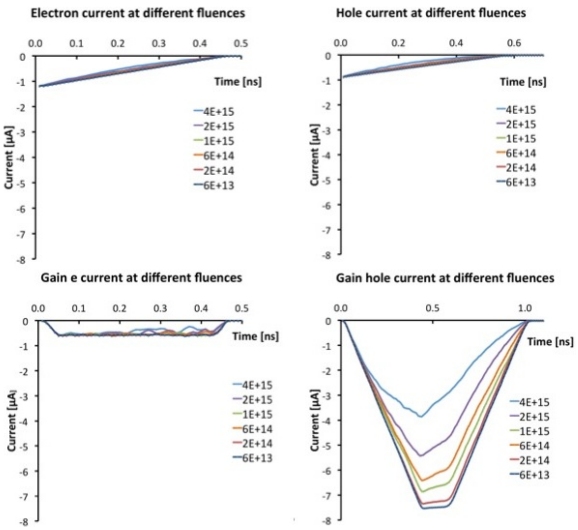

Figure 2: Variation of the different components (electron, holes, gain electrons, gain holes) of the current signal of an irradiated 50 μm silicon detector with fluence

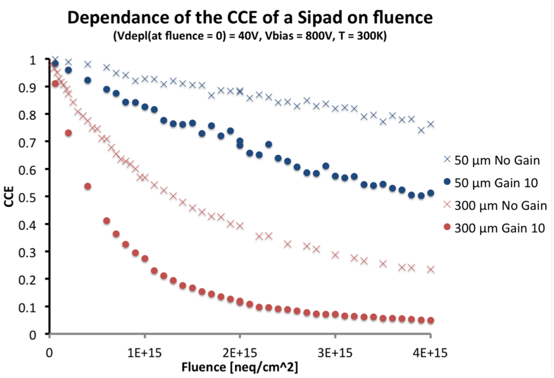

Figure 3: Variation of the charge collection efficiency of silicon detectors of vapours thickesses and gain values with fluence

each other. In the context of this work, the values determined by Kramberger et al. [6] have been chosen and are reported in Table 1, being considered to be the most complete as they address both irradiation by different particle kinds (which, as mentioned, shows slight differences in the trapping time), and the variation of β with temperature, which has been parametrised as:

$$\beta(T) = \beta(T_0)(\frac{T}{T_0})^K \tag{6}$$

tha values of the parameter K are also reported in Table 1 and $T_0 = 263K$.

On the basis of this description, 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.

It can be clearly seen by the simulated CCE curves that for a standard thickness of 300 μm the gain effects are completely cancelled for fluences above 10^{15} neq/cm^2 even without keeping in count any depletion of the extra gain layer. Thus, to minimise radiation destructive effects thinner detectors should be the goal: with the same trap concentration, the shorter drift undergone by the electrons results in a lower reduction of the charge collection efficiency (as the trapping probability per unit length remains the same, but the path of the electrons before collection is shorter). This is already an aim for future applications as, amongst other advantages, thinner detectors would provide both lower noise and and faster signal (as the carriers would undergo shorter drift).

2.2 Limitations and Future Developments

It's important to notice that the simulations presented so far don't provide a complete description of the behaviour of an irradiated detector.

The most important change to still be implemented is an account of the evolution of the effective charge density. Not only the mentioned double junction effect would completely modify the output in terms of the electric field distribution, but the initial dopant removal, although negligible for traditional detectors, is being proven to be crucial in the description of the performance of detectors with internal gain such as LGADs and UFSDs. In particular, an almost complete removal of the doping layer within the first $10^{14} neq/cm^2$ is being observed, such that the detector's performance becomes comparable to that of traditional ones [11]. Furthermore, the effects on the depletion voltage are complex and surely non negligible. If the non uniformity of the doping concentration is ignored to a first approximation, and V_{depl} is still considered as a good description of N_{eff}, it becomes clear that the dramatic increase in doping observed for high fluences has a noticeable impact on the detector's performance as it requires much higher voltages to achieve full depletion and thus a full operation. If the new linear dopant distribution is kept in count, on the other hand, although higher voltages will still be necessary to achieve full depletion, the depletion voltage itself would cease to be a meaningful quantity as it would no longer provide a correct account for the effective doping concentration. Lastly, type inversion, although not of great interest in terms of practical applications as it is already being successfully dealt with, still represents a relevant phenomenon to be included in a valid simulation.

The path to be undertaken to account for the effects just described has not yet been finalised, but various options are being considered and will be tested. If the double junction effect is to be kept in count, the current approach consisting of extrapolating the electric field distribution from the depletion voltage would no longer bel valid, and a new method, perhaps starting from the initial depletion voltage to calculate the initial doping concentration, and applying the Hamburg model to account for its evolution, would be needed. An attempt to model the quadratic electric field distribution which has proven effective is that of dividing the detector in three zones of different linearly varying dopant concentration, and calculating the electric field for each of them with the use of Poisson's equation, which would result into three different parabolic field zones that, provided an appropriate tuning of the parameters used in the simulation, have proved to show a close resemblance to the observed electric field distributions [12].

As mentioned, irradiation by charged and neutral hadrons has different outcomes, specially concerning the effective doping concentration. The choice between the two is most likely to be implemented in the GUI for the next version of Weightfield.

A second pressing issue concerns the incompleteness of the model describing charge trapping. As already mentioned, the value of the proportionality constant β has been experimentally determined, and not all studies are in complete agreement. Nevertheless, this has been proven to be a negligible matter, as simulations with all values found in the literature have been conducted without any relevant difference in the current output. A much more relevant issue is that concerning the influence of the applied voltage on the current degradation: for high voltages and fluences a parametrisation of the trapping time just in function of the fluence no longer provides a good description without a second a voltage dependent term. In fact, rather than on the voltage, the dependance of the trapping probability is likely to be on the electric field, but the only effective parametrisation found in the literature up to the present time is that by J. Lange et al. [14]:

$$\tau_{eff} = \tau_0 + \tau_1 \frac{(V_{bias} - V_{depl})}{100V} \tag{7}$$

This description is still significantly limited as it was made ad hoc to fit the experimental results of the study, which was conducted for a very restricted number of fluence values and detector types. It would not be therefore appropriate to include it in the model yet, although it provides a good starting point for future reasoning.

Charge multiplication effects have also been observed for high fluences and voltage, and are still not correctly accounted for [15].

Oxygenation of the material is an important variable to be kept in count: although no influence has been observed on either the trapping probability or the leakage current [6] [16], it has been proven to significantly reduce donor removal [2].

Another relevant phenomenon that hasn't been addressed is that of annealing, a behaviour for which the primarily produced defects are subject to changes after long term storage of the detector at room temperature (or shorter time storage at high temperature). The annealing behaviour of silicon has been intensively studied and is now fairly well known; there could be the possibility of including it in the simulation by adding two "Annealing Time" and "Annealing Temper ature" user input entries. Nevertheless, so far it hasn't been treated because Weightfiled2 is a simulator aiming to describe the performance of a detector when in usage, and that of annealing is a behaviour implying absence of radiation incident on the detector.

An addition of smaller relevance is that concerning the carrier mobility. This quantity has been observed to have a moderate fluence dependant variation, and a parametrisation (just for what concerns the electrons mobility) has been proposed by J.V.Vaitkus et al. [13]. Although the implementation of such parametrisation has led to little variation in the signal output, if further investigation of this matter provides significant results, it will most likely be considered in the next version of the software.

Finally, although up to the present the effect of leakage current have been entirely neglected, it would probably be considered for a future upgrade to include such component b adding it to the output current, and, in case, it would be likely for the parametrisation presented in the introduction to be adopted to account for irradiation effects.

3 Conclusion

The impact of radiation damage on silicon detectors can be described by three main changes in (i) the effective doping concentration, (ii) the leakage current, and (iii) the charge collection efficiency. The last issue has been addressed and implemented in the simulation program Weightfield2, which is aimed at describing the operation of silicon and diamond detectors. A trapping model based on an exponential decay of the current output has been included in the program and led to results in general agreement with experimental observations for what concerns the degradation of current with fluence. Nevertheless, the model still presents numerous limitations, amongst which the most relevant are the absence of a description of the effects of the change in doping concentration and distribution, which leads to increase in depletion voltage, type inversion and double junction effects, and the incompleteness of the parametrisation of the trapping time which should contain a voltage dependent term, in addition to the fluence dependent one.

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