Nuclear Instruments and Methods in Physics Research A 658 (2011) 70–72

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Simulation of displacement damage for silicon avalanche photo-diodes

Adnan Kılıç *, Ercan Piliçer, İlhan Tapan, Emin N. Özmutlu

Uludağ University, Department of Physics, 16059 Bursa, Turkey

ARTICLE INFO

Available online 6 June 2011

Keywords:
Radiation damage
Avalanche photo-diode
Geant4 simulation

ABSTRACT

The silicon avalanche photo-diodes (APDs) in the CMS barrel electromagnetic calorimeter will be exposed to an integrated neutron fluence of about 2×10^{13} n/cm^2 over 10 years of operation. High neutron fluences change the electrical properties of silicon detectors. The changes are proportional to the non-ionising energy loss in the APDs. Using the Geant4 toolkit, we have calculated the non-ionising energy loss as well as the rate of generation of primary defects in the APDs, for the expected neutron fluence.

1. Introduction

The CMS detector at the LHC is operating in a severe radiation environment. Hamamatsu S8148 silicon avalanche photo-diodes (APDs) working in proportional mode have been chosen as photodetectors for the PbWO$_4$ crystals in the barrel part of the CMS electromagnetic calorimeter. The APDs consist of successive layers of p$^+$-, p-, n-, n$^-$- and n$^+$-type silicon layers, as shown in Fig. 1. The properties and working principles of the structure are given in [1]. The integrated neutron fluence at the location of the APDs is expected to be about 2×10^{13} n/cm^2 after 10 years of operation i.e. 500 fb^{-1}. As a result, APD performance will significantly degrade, thus reducing the calorimeter resolution. The degradation is caused by defects in the form of silicon atoms knocked out of their original position by high-energy neutrons. This leads to an increase in the dark current and a change in the effective doping concentration. As the electric field in the depletion region is related to the effective doping concentration, high neutron fluences modify the avalanche gain of the APD. Such defects can also act as trapping centres and can change APD parameters such as the charge collection efficiency and quantum efficiency.

2. Radiation damage

When neutrons of sufficient energy collide with lattice silicon atoms, one or more heavy recoils called primary knock-on atoms (PKA) can be formed. These move from their lattice positions into (self-)interstitial positions. Their unoccupied initial positions act as vacancies. If the recoil energy is large enough, further atoms may be displaced. The process continues as long as the energy of the recoils is higher than the threshold for atomic displacements. This cascade can create a cluster of vacancies and interstitials of considerable spatial extent [2].

In case of elastic scattering of neutrons, the recoil energy is given by

$$E_{\mathrm{R}} = \frac{4A}{(1+A)^2}\cos^2\theta E_{\mathrm{n}} \tag{1}$$

where A is the atomic mass of the target, θ the scattering angle of the recoil relative to the direction of the incoming neutron, and E_{n} the incoming neutron energy [3].

The rate of energy loss in the form of atomic displacements as a particle traverses a material is described by the so-called non-ionising energy loss NIEL [4] which is defined by [5]:

$$\mathrm{NIEL}(E) = \frac{N_A}{A}\sum_i \mathrm{L}(T)T\,\mathrm{d}\sigma_i(E,T). \tag{2}$$

Here, $\mathrm{d}\sigma_i(E,T)$ is the differential cross-section for a particle with energy E to create a secondary particle with kinetic energy T, $\mathrm{L}(T)$ is the Lindhard partition function, N_A is the Avogadro number and A is the molar mass.

The concentration of primary radiation-induced defects per unit fluence (CPD) in silicon is defined by I. Lazanu and S. Lazanu [6] as the sum of the concentration of defects resulting directly or indirectly from the neutron interaction:

$$\mathrm{CPD}(E) = \frac{1}{N_A}\frac{N_i^{\mathrm{Si}}A_i^{\mathrm{Si}}}{2E_i^{\mathrm{Si}}}\mathrm{NIEL}(E) \tag{3}$$

where E is the kinetic energy of the incident particle, N_i^{Si} the silicon atom number density, A_i^{Si} the silicon atomic number, E_i^{Si} the average threshold energy for displacements in silicon and N_A the Avogadro number.

---

* Corresponding author.
E-mail address: adnank@uludag.edu.tr (A. Kılıç).

0168-9002/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2011.05.073

The Lazanu CPD model assumes that vacancies and interstitials always occur in pairs which are uniformly distributed through the silicon. Defects are either produced by the incident particle or thermally, the sum of the two contributions is called the generation rate:

$$G = G_R + G_T. \tag{4}$$

The generation rate by irradiation G_R is calculated as

$$G_R = \mathrm{CPD}(E)\phi(E) \tag{5}$$

where $\phi(E)$ is the flux of incident particles [6].

3. Simulation and validation

We have used Geant4 version 9.3 with the G4NDL 3.13 neutron-data library [7] for our simulations. As physics list we have chosen the G4NeutronHPElastic high-precision neutron model, which is suitable for the 1 MeV elastic neutron collisions which we wish to study.

Elastic scattering is virtually the only displacement producing process for 1 MeV neutrons hitting silicon. Natural silicon is composed of 92.2% ^{28}Si, 4.7% ^{29}Si and 3.1% ^{30}Si [8] with total (or elastic) neutron cross-sections at 1 MeV according to JENDL-4.0 [9] of respectively, 4.68 b, 2.16 b and 2.09 b. We understand the uncertainty of the cross-sections does not exceed 5%. The (n,Si) cross-section has numerous resonances around 1 MeV for all three isotopes, but at 1 MeV the cross-section is almost entirely elastic [9]. The density of natural silicon is 2.33 g/cm^3 [8]. The weighted average cross-section of 4.45 b equates to a mean free path of 4.52 cm and is compatible with our Geant4 simulations where the fraction of 1 MeV neutrons that interact in 100 μm of natural silicon is 0.00227.

The energy sharing between displacement and ionisation was modelled according to the Lindhard theory. Weller et al. [5] have introduced a screened Coulomb scattering module in Geant4 to compute the non-ionising component of the energy deposited in semiconductor materials. We have used this module to compute

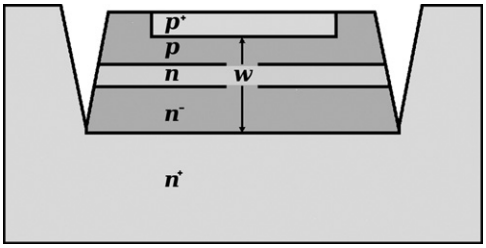

Fig. 1. Hamamatsu S8148 silicon APD structure, *w* is the depletion region in which an electric field is established. The dimensions are distorted.

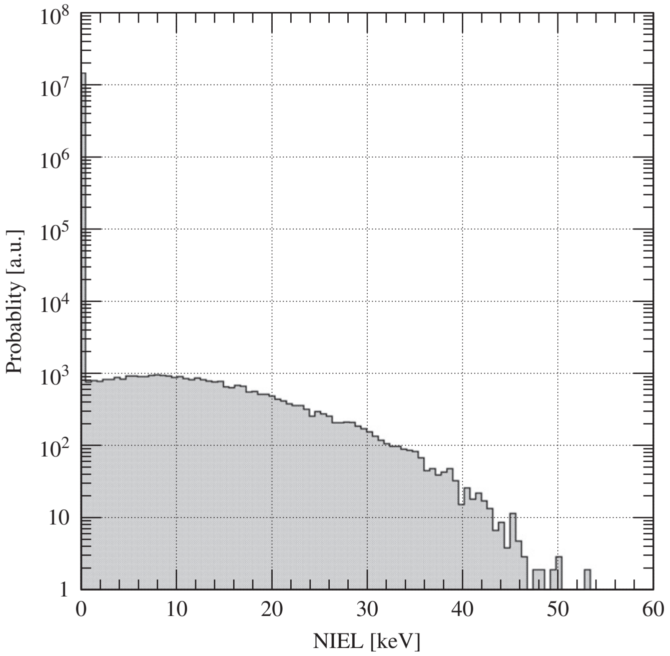

Fig. 2. Distribution of NIEL per 1 MeV neutron. Incident neutrons interact with the APD material producing recoil atoms which dissipate their energy in the form of a cluster of lattice damage. The damage is proportional to the NIEL.

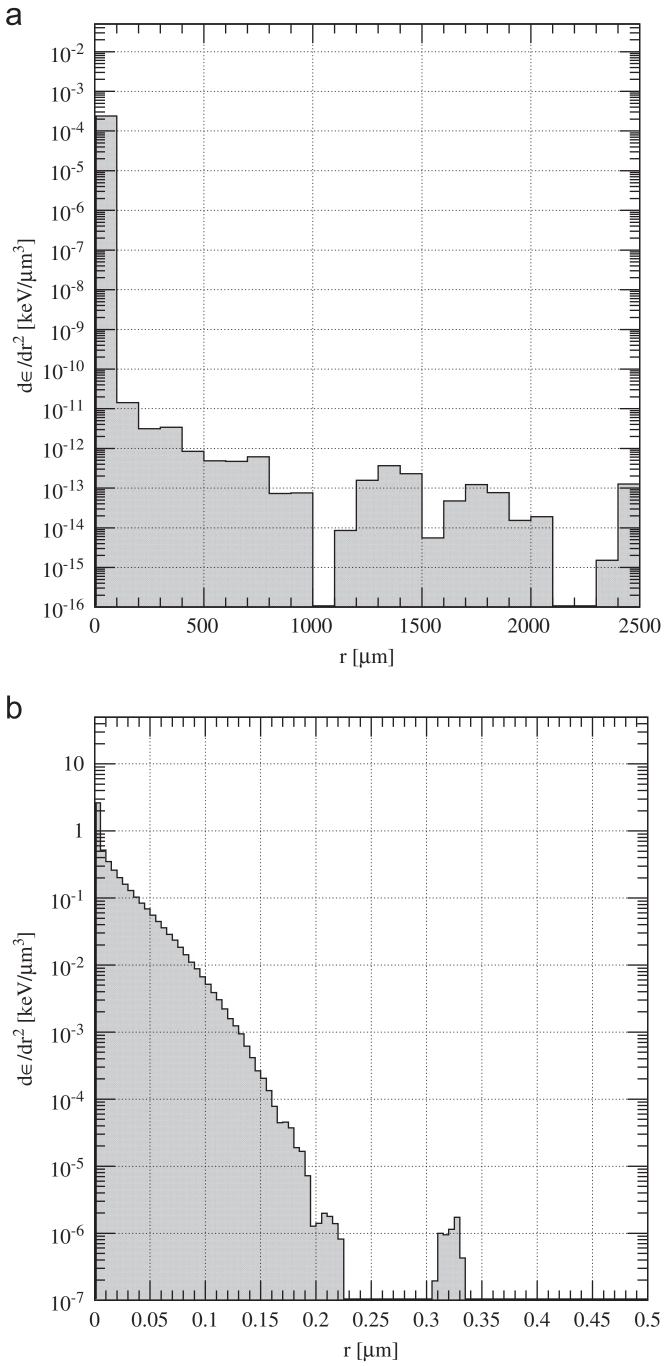

Fig. 3. Top: Volume density of NIEL per 1 MeV neutron as a function of the lateral distance from the neutron track in an APD. Bottom: detail of immediate vicinity of the neutron.

the non-ionising component of the energy deposition resulting from PKAs.

The maximum non-ionising energy loss observed in Geant4 of 55 ± 2 keV for a 1 MeV neutron, Fig. 2, is compatible with a Lindhard partition function of 0.46 [10], the uncertainty of which we estimate to be ± 0.05 judging by the experimental data, multiplied with the maximum kinetic energy of $4A/(A+1)^2 E_n =$ 133 keV for a Si recoil from an $E_n = 1$ MeV neutron.

The mean non-ionising energy loss per 1 MeV neutron calculated by Geant4 is 28.9 eV, which is to be compared with the NEMO value of 25.9 eV [11] and the value of 47.5 eV calculated by Akkerman et al. [12].

In the Geant4 simulation, see Fig. 3, the non-ionising energy is almost entirely deposited within a radius of 0.23 μm from the neutron track. This corresponds to the range of silicon recoils in silicon of 0.21 μm found in Tino Heijmen's survey [13]. At larger radii, the NIEL density decreases slowly with radius. Nearly all damage therefore occurs in the immediate vicinity of the neutron track.

In the simulation, the CPD is 70/cm with an error of approximately 10%, to be compared with the Lazanu value of 100/cm [14]. From this, we derive $G_R = 1.40 \times 10^{15}/\text{cm}^3$ for a 1 MeV equivalent integrated neutron fluence of $2 \times 10^{13}\ \text{n/cm}^2$.

Vacancies and interstitials are not stable: with time, displaced atoms may return to their original positions or to other vacancies. Dark current is an indicator of the defect concentration, and indeed diminishes with time when the silicon is no longer irradiated. The recovery process has been measured to take between 100 and 150 days, depending on the temperature [15]. The process, and its temperature dependence, has been reproduced by calculations [16]. Therefore, the performance degradation will in general be smaller than indicated by the CPD.

4. Summary

Using Geant4, we have calculated the average non-ionising energy loss per neutron in silicon APDs to be 28.9 eV. The CPD in the APD without annealing is found to be 70/cm. The corresponding generation rate G_R is $1.4 \times 10^{15}/\text{cm}^3$ for a 1 MeV equivalent integrated neutron fluence of $2 \times 10^{13}\ \text{n/cm}^2$. These values suggest that considerable damage will occur. In reality, because of the decrease in the CPD with time after irradiation, the density of defects in the detector is less severe. In this work, we studied the CMS APDs because they are an example of a detector for which experimental radiation damage data is available. As member of the Turkish Accelerator Center (TAC) project [17], our group conducts simulations of the radiation damage to the semiconductor parts of the proposed TAC particle factory detector.

Acknowledgments

The authors would like to acknowledge Dr. Marcus Mendenhall and Dr. C. Inguimbert for their valuable advice. We gratefully acknowledge assistance of Sanja Damjanovic and Rob Veenhof.

References

[1] K. Deiters, et al., Nucl. Instr. and Meth. A 453 (2000) 223.
[2] I. Lazanu, S. Lazanu, Rom. Rep. Phys. 57 (2005) 342.
[3] G.F. Knoll, Radiation Detection and Measurement, John Wiley & Sons Inc., 2000.
[4] I. Jun, et al., Nonionizing Energy Loss (NIEL) for Protons, 2003.
[5] R.A. Weller, et al., IEEE Trans. Nucl. Sci. NS-51 (2004) 3669.
[6] I. Lazanu, S. Lazanu, Physica Scripta 67 (2003) 388.
[7] Geant4 collaboration, Geant4—a simulation toolkit.
[8] Mark Winter, WebElements: the periodic table on the web.
[9] K. Shibata, et al., J. Nucl. Sci. Tech. 48 (2011) 1.
[10] A.R. Sattler, Phys. Rev. 138 (1965) A1815.
[11] C. Inguimbert, R. Gigante, IEEE Trans. Nucl. Sci. NS-53 (2006) 1967.
[12] A. Akkerman, et al., Radiat. Phys. Chem. 62 (2001) 301.
[13] T. Heijmen, Radiation-induced soft errors in digital circuits—a literature survey, 2002.
[14] I. Lazanu, S. Lazanu, Silicon detectors for the next generation of high energy physics experiments: expected degradation, arXiv:physics/0512275v1, 2005.
[15] S. Baccaro, et al., Nucl. Instr. and Meth. A 426 (1999) 206.
[16] I. Lazanu, S. Lazanu, Silicon detectors: damage, modelling and expected long-time behaviour in physics experiments at ultra high energy, Nucl. Instr. and Meth. A 572 (2007) 297 Frontier Detectors for Frontier Physics—Proceedings of the 10th Pisa Meeting on Advanced Detectors.
[17] S. Ozkorucuklu, et al., The status of Turkish Accelerator Center Project, in: First International Particle Accelerator Conference, IPAC10, held in Kyoto, Japan, 2010.