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Comparison of radiation damage parameter values for the widely used semiconductor gamma detector materials in wide energy range

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HIGHLIGHTS

- DPA values for 3 semiconductor materials were simulated by FLUKA Monte Carlo code.
- Widely used 26 primary photon energies were preferred.
- Numbers of displaced atoms (NDA) values versus energy were illustrated.
- Germanium with the highest average NDA value was observed.

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ABSTRACT

Number of displaced atoms (NDA) values for 3 different semiconductor detector materials (Ge, Si, and GaAs) was reviewed at 26 different primary energies emitted from 9 radiation sources (^{241}Am, ^{133}Ba, ^{109}Cd, ^{57}Co, ^{60}Co, ^{137}Cs, ^{152}Eu, ^{55}Fe and ^{153}Gd) widely used in the literature. FLUKA Monte Carlo code was used to simulate interactions between X–gamma rays and semiconductor detector materials. Germanium has the highest average NDA value in the studied three semiconductors.

1. Introduction

X rays and gamma rays can be counted by recording interactions with matter. Different detectors have been used to trace X rays and gamma ray and their energies such as gas filled detectors, scintillation detectors and solid-state detectors. In solid-state (semiconductor) detectors, generated charges by photon interactions with matter are counted directly. In these systems different semiconductor materials have been used as target material (sensitive volume). Electron–hole pairs occur after interactions between gamma rays and target semiconductor material. Charged electrodes collect these pairs. These pulses give information about numbers, times of arrival, energies, and types of particles. Energy resolutions of semiconductor detectors are better than those of other detector types. A typical semiconductor detector arrangement can be seen in Fig. 1. The most commonly used semiconductor materials in the detector designs are germanium, silicon, cadmium telluride, and gallium arsenide crystals. Also studies about CZT (CdZnTe) based detectors and thallium-based materials are remarkable recently.

In the literature, studies about element and compound semiconductor radiation detectors have recently become widespread. Room temperature compound solid state detectors were introduced in a paper in 1990s (McGregor and Hermon, 1997). Recently, several analyses about CdTe (Cevik et al., 2008; Bulycheva et al., 2009), CdZnTe (Kim et al., 2011; Auricchio et al., 2001; Tan et al., 2011; Wangerin et al., 2011; Bale, 2010), TlBr (Kim et al., 2011; Hitomi et al., 2009), and HgI_2 (Kargar et al., 2011; Saleno et al., 2011) have been made. Also thallium-based new generation compound detectors such as Tl_6I_4Se, Tl_3AsSe_3, $TlGaSe_2$, and Tl_4HgI_6 have been improved (Kahler et al., 2011; Liu et al., 2011).

Radiation damage is an important issue for radiation detectors. Displacement per Atom (DPA) is a useful radiation damage parameter recently implemented in the FLUKA Monte Carlo code (Fasso et al., 2010, 2011; Smirnov et al., 2013). In this paper we have simulated X–gamma rays interactions with above mentioned semiconductor detector materials by using FLUKA Monte Carlo code and the number of displaced atoms (NDA) values was given. Results were evaluated in terms of photon energies and semiconductor types.

2. Methodology

FLUKA is a Monte Carlo electromagnetic and particle radiation transport code widely used in dosimetry, medical physics, nuclear

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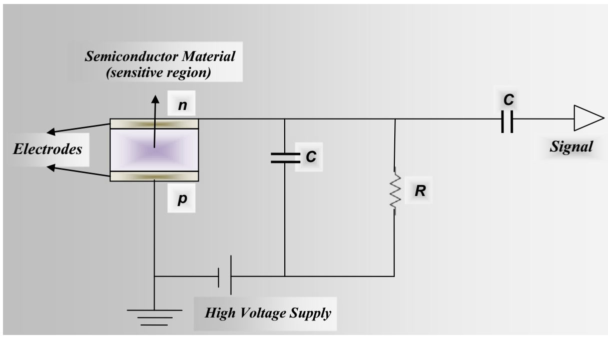

Fig. 1. Typical semiconductor detector configuration.

reactor design, detectors, astroparticle physics, etc. (Battistoni et al., 2007; Ferrari et al., 2005). It can simulate interactions between different radiation types and matter from keV to PeV energies. Recently, especially for the last 5 years, studies using FLUKA Monte Carlo code have increased (Kajimoto et al., 2012; Datz et al., 2011; Agosteo et al., 2011; Rollet et al., 2009; Obryk et al., 2008; Korkut et al., 2011, 2012; Korkut and Korkut, 2013). In the FLUKA code, radiation damage in materials (especially semiconductors) has been implemented using DPAs (Displacements per Atom). DPA means the amount of radiation damage in materials. For example if DPA is equal to 5, each atom in the material has been displaced on an average 5 times in its structural lattice. DPA value depends on the number of atoms per cm^3 (ρ_A), number of particles per interaction channel (N_i), and Frenkel pairs per channel (N_i^F) as shown in Eqs. (1) and (2) (A is the mass number; N_A is Avogadro's number, and ρ is density) (Fasso et al., 2011).

$$DPA = \frac{1}{\rho_A}\Sigma_i N_i N_i^F \quad (1)$$

$$DPA = \frac{A}{N_A \rho} N_F \quad (2)$$

$$N_F = \kappa \frac{\xi(T)T}{2E_{th}} \quad (3)$$

Frenkel pairs, mentioned above in Eq. (3) (Kinchin and Pease, 1955; Norgett et al., 1975), are related to displacement of atoms or ions in the lattice by motion. After this motion, a vacancy is formed in the former site of displaced atom or ion (Fig. 2). In Eq. (3), κ is the displacement efficiency (0.8), $\xi(T)$ is the Lindhard partition function (nuclear stopping power/stopping power-fraction of stopping power; Lindhard et al., 1963), T is the kinetic energy of the PKA(primary knock-on atom), and E_{th} is the displacement damage energy threshold (eV). In our FLUKA input file, 3 different semiconductor detector materials were described in the same dimensions ($0.5 \times 0.5 \times 0.2$ cm^3). Semiconductor materials used in the radiation detectors are generally in 1–20 mm thickness range (Lucas, 1991). So, we have chosen dimension of our materials as $0.5 \times 0.5 \times 0.2$ cm^3. in the prepared input file. In the simulations 26 different X–gamma ray primary energies were selected. Photon beam used in our simulations is uniformly distributed, pencil-like and in the z-direction. 1 keV particle threshold for photons was entered as suggested by Fasso et al., 2011. Damage threshold energy is the value of the threshold displacement energy averaged over all crystallographic directions or a minimum energy to produce a defect. Damage thresholds for each studied material used in the simulations are given in Table 1. After simulations, DPA values were read from USRBIN output file. In the FLUKA implementation, Displacements per Atom (DPAs) have been expressed as average DPAs in each bin per unit primary weight. To obtain NDA values, we multiplied FLUKA DPA scores to the number of atoms in the crystal volume to obtain NDA values (Guthoff et al., 2014).

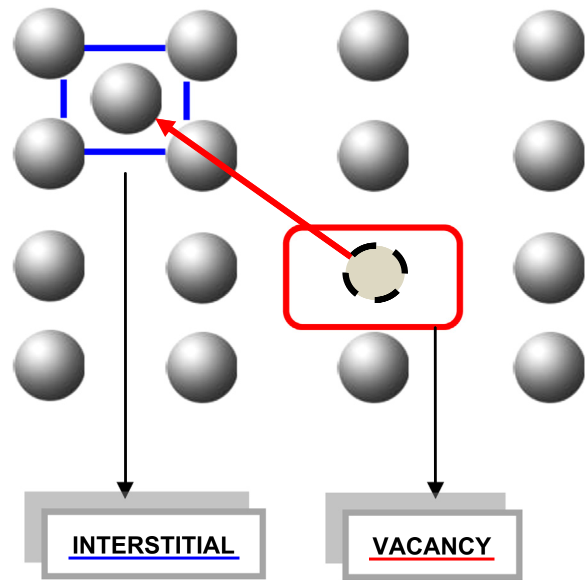

Fig. 2. Formation of vacancies in lattice.

Table 1
Damage threshold energies and physical densities of the studied semiconductors.

Material	E_d (eV)	Density (g/cm^3)
Ge	20[a]	5.32
Si	25	2.33
GaAs	9.9[b]	5.32

[a] Jun (2004).
[b] http://www.holbert.faculty.asu.edu/eee560/RadiationEffectsDamage.pdf.

$$NDA = DPA * N_{AVOGADRO} x \rho x V/A \quad (4)$$

where A is the mass number; N_A is Avogadro′s number, ρ is density, and V is *volume of detector material*)

Detailed information about FLUKA code can be found in the code's web page (www.fluka.org).

3. Results and discussion

FLUKA Monte Carlo simulations were performed to see radiation damage levels of 3 different semiconductor materials used in the solid state detector structures at 26 different photon energies. Simulation results were evaluated with two different ways: energy dependent and semiconductor type dependent.

3.1. Results depending on energy

3.1.1. 1–100 keV energy region

In this energy region 10 different gamma energies (5.9, 6.515, 21.9, 22.1, 24.9, 59.54, 69.7, 81, 88, and 97.4 keV) were simulated, emitted from 5 different sources (^{55}Fe, ^{109}Cd, ^{241}Am, ^{133}Ba, and ^{153}Gd). Looking at the results in this range (Table 2), Ge is viewed as having the highest average NDA values. Ge is followed by Si and GaAs respectively.