Jurnal
Teknologi

Full Paper

MECHANISM OF BIJUNCTION SEMICONDUCTOR DEVICE DAMAGE INDUCED BY HEAVY PARTICLES

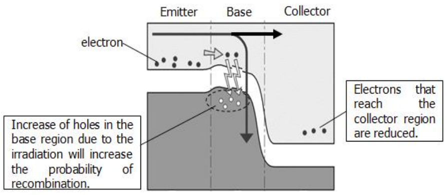
Saafie Salleh[a], Fuei Pien Chee[a*], Haider F. Abdul Amir[b]

[a]Physics with Electronic Department, Faculty of Science and Natural Resources, University of Malaysia Sabah, Sabah, Malaysia
[b]School of Physics and Materials, Faculty of Applied Science, University of Malaysia Mara, Shah Alam, Selangor, Malaysia

Article history
Received
15 June 2015
Received in revised form
1 October 2015
Accepted
13 October 2015

*Corresponding author
fpchee06@ums.edu.my

Graphical abstract



Abstract

The physical phenomena associated with the stopping of energetic ions in semiconductor materials have always been a subject which receives great theoretical and experimental interest. Consequently, bombardment of high energy particles and high energy gamma (γ) rays causes potential hazards to these electronic systems. These effects range from degradation of performance to functional failure that can affect the system operations. Such upsets becoming increasingly likely as electronic components are getting more sophisticated while decreasing in size and moves to larger integration. In this paper, the penetration of gamma rays, utilizing Cobalt-60 (Co-60)) into bipolar junction transistor (BJT) is being simulated using the program simulation SRIM. From the findings, it is observed that the penetration of Co-60 ions into the simulated BJT leads to production of lattice defects in the form of vacancies, defect clusters and dislocations. These can alter the material parameters and hence the functional properties of the devices.

Keywords: Gamma (γ) rays, bipolar junction transistor (BJT), radiation damage

Abstrak

Fenomena fizik penghentian ion bertenaga dalam bahan semikonduktor merupakan bidang yang sentiasa menjadi tumpuan dalam penyelidikan. Pembedilan zarah yang bertenaga tinggi serta sinar gama (γ) bertenaga tinggi berpotensi untuk membawa kesan yang memudaratkan kepada sistem elektronik. Antara kesan tersebut termasuklah degradasi prestasi dan kegagalan fungsi yang boleh menjejaskan operasi sistem. Masalah ini menjadi serius apabila komponen elektronik kini adalah jauh lebih canggih namun saiznya semakin berkurangan dan tumpat dengan integrasi yang tinggi. Dalam persembahan kertas ini, penembusan sinar gamma, dengan menggunakan Cobalt-60 (Co-60) dalam transistor simpang dwikutub (BJT) disimulasi dengan menggunakan program simulasi SRIM. Daripada hasil kajian, didapati bahawa penembusan ion Co-60 dalam BJT boleh menyebabkan kecacatan kekisi dalam bentuk penghasilan kekosongan, kecacatan berkelompok dan penyesaran. Ini boleh mengubah parameter bahan dan sifat fungsi peranti tersebut.

Kata kunci: Sinar gama (γ), transistor simpang dwikutub (BJT), kerosakan sinaran

1.0 INTRODUCTION

Semiconductor devices serve as the foundation of the electronic industry, with global sales of exceeding one trillion dollars since 1998. The life span of these semiconductor devices greatly depends on the radiation environment and also their operating conditions. Furthermore, there is a growing tendency in using non-traditional parts as replacements for existing high reliability space qualified parts. Several devices procured as off-the-shelf parts, packaged in plastic, were evaluated for their radiation sensitivity and resistivity. In general, the effects caused by radiation can be categorized into four classes: Electromagnetic Pulse (EMP) effects, high dose rate effects, Single Event Upsets (SEU) and total dose effects [1].

The parameters that give effect to the formation of radiation damage are the ion mass, the target temperature during irradiation, ion flux (number of implanted ions per unit area and time), the ion's energy and the ion's fluence (number of ions per unit area) [2]. The energy transferred to the crystal lattice is strongly determined by the ion mass. The ions can lose their energy by two ways which are the electronic energy loss through the excitation of electronic system and nuclear energy loss through nuclear collisions with the target atoms [3]. The incident ions will finally come to rest at certain depth, z.

Gamma (γ) ray is a stream of high-energy electromagnetic radiation given off by an atomic nucleus undergoing radioactive decay [4]. Gamma rays have energies typically in the range of 0.1 to 10 MeV, and thus corresponding wavelength between 10^4 and 100 femtometer (fm). These wavelengths are far shorter than those of the other types of electromagnetic radiations. Gamma rays are the most energetic form of light and are produced by the hottest regions of the universe. They are also produced by violent events such as supernova explosions or the destruction of atoms, and by less dramatic events, for example, the decay of radioactive material in space [5]. Things like supernova explosions, neutron stars, pulsars, and black holes are all sources of celestial gamma rays. Due to the high energy of gamma grays, gamma photons travel at the speed of light and can cover hundreds to thousands of meters in air before spending their energy.

Gamma rays can pass through many kinds of materials [6]. This results the straight line travelling through matter and deposition of energy in short distance. When a Co-60 ion slows down and comes to rest in a crystal, a number of collisions are made with the lattice atoms. In these collisions, lattice atoms which are displaced by the incident ions are known as primary knock-on atoms (PKAs). The energy required to displace the lattice atom represents the displacement threshold and is called the displacement energy, E_d. The PKAs can in turn displace other atoms and ends up in creating a cascade of atomic collisions. This leads to the lattice disorder on the region around the ion track [7].

The energies of the large majority of gamma rays used for applications are normally between 50 keV and 3 MeV. Alpha (*α*) and (*β)* particles are frequently completely absorbed in the material through which they travel; the intensity of beams of gamma rays is attenuated exponentially, while the extent of attenuation is a useful parameter for numerous applications [8].

In this paper, the damage induced to BJT by Co-60 ions using SRIM-TRIM software package will be presented. BJTs were being studied as they show excel applications in analogue or mixed signal ICs and Bipolar Complementary Metal-Oxide-Semiconductor (BiCMOS) circuits due to their high transconductance, linearity, low noise and excellent matching characteristics. Moreover, BJTs are widely used in amplifying, regulating or switching applications in space systems [9].

2.0 SIMULATION DETAILS

SRIM is a computer simulation that uses Monte Carlo method and it contains TRIM calculation. Monte Carlo method is a class of computational algorithms that rely on repeated random sampling and probability statistics to compute their results [10]. This method is ideal for calculation by a computer and tends to be used when it is impracticable to compute an exact result with a deterministic algorithm. It is applicable in ion-solid interactions and has a number of distinct advantages over analytical calculations based on transport theory [11].

The SRIM-TRIM simulation results are important as they explain the transport of the ion in the target at different energy levels whereas for the real irradiation exposure, the energy of the incidence ion is constant. Besides, this simulation is used to calculate the range of ions in matter using collisions of ions-atoms. It also can calculate the 3D spreads of ions as well as all the kinetic phenomena that are related with the loss of energy: damage of the target, sputtering, ionization and phonon production. The enumeration of the range of ions in matter and the damage event in the target during the slowing-down process can be done using TRIM [12]. The results obtain in this simulation have shown excellent agreement with a wide range of experimental data for ions with energies below 1 MeV.

This simulation can show the full animation of the penetrating process, the recoil cascades and also the mixing of target atoms. In order to make precise evaluations of the physics of every single encounter between the ion and target atom, the calculation is triggered for one ion at a time. The calculation runs even it is interrupted a while and the output results can be saved and used later. The calculation period is varied for different ions, which may range from a second to a few minutes for each ion.

By the simulation of detailed calculation with full damage cascades, the plots of ion trajectories, depth vs. Y-Axis, depth vs. Z-Axis, transverse view, ionization, phonons, collision events, atom distributions and energy to recoil can be obtained. The flowchart of the simulation process is as shown in Figure 1.

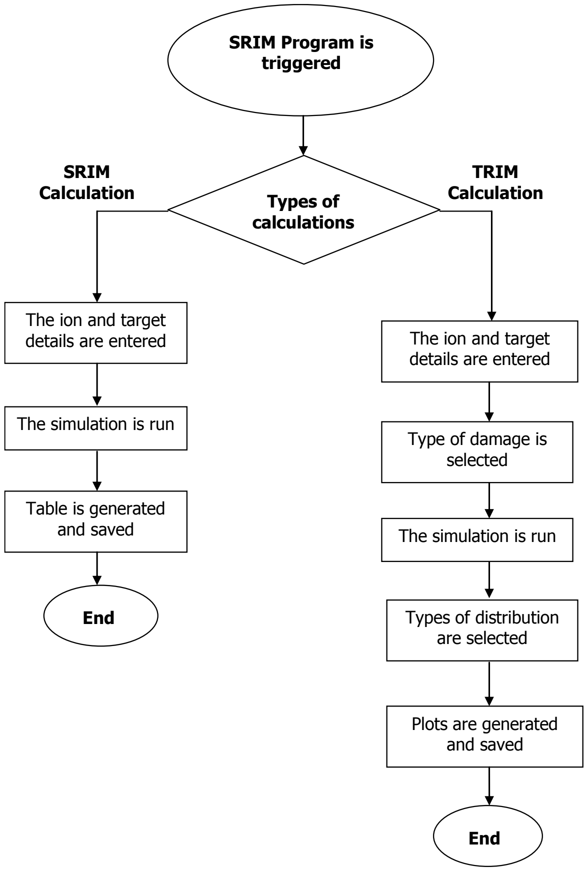


Figure 1 Flow chart of SRIM-TRIM simulation process

In this research, the interaction between ^{60}Co ions with the BJT at different energy level is simulated. The calculation is done by using SRIM-TRIM Simulation using full damage cascade phenomena. This study is done by quantitative analyzing of energy loss of ^{60}Co ions while penetrating the silicon matter. The energies of the incidence ^{60}Co ions are varying from 100 keV up to 10 MeV. The number of incidence ions for each simulation is 2,000 ions. The damage induced to npn BJT is simulated using the typical cross section as shown in Table 1.

Table 1 Cross section of npn BJT

Layer	Width (Angstorm)	Density (g/cm3)
n-Si	20,000	2.0715
p-Si	10,000	2.3357
n-Si	20,000	2.0715

3.0 RESULTS AND DISCUSSION

When the ^{60}Co ion penetrates into the target layer, it undergoes a series of collisions with the atoms and electrons in the target. The stopping of the ^{60}Co ion, the collision sequence and subsequent ion deflection in the target materials are stochastic process. In these collisions, ^{60}Co ion loses its energy at a rate of *dE/dx* of a few 100 electrons - volts per nanometer, depending on its incident energy [11]. The range, *R* can be determined by the rate of energy loss along the path of the ion

$$R = \int_{E_{Co}}^{0} \frac{1}{dE/dx} dE. \tag{1}$$

where E_{Co} = is the incident energy of the ^{60}Co ion as it penetrates the solid.

R is defined as the total distance that the projectile travels in coming to rest. However, in most of the conditions and applications, the projected range, R_p, is the quantity of interest. R_p is the total path of length of the projectile measured along the direction of incidence and can be as expressed in (2).

$$R_p \cong \frac{R}{1+(M_2/3M_1)} \tag{2}$$

where M_1 is the atomic mass of ^{60}Co ion (60 amu) and M_2 is the atomic mass of the targeted semiconductor material. The atomic mass of silicon is 28 amu. The projected range of ^{60}Co ion in silicon is as shown in the plot of Figure 2.

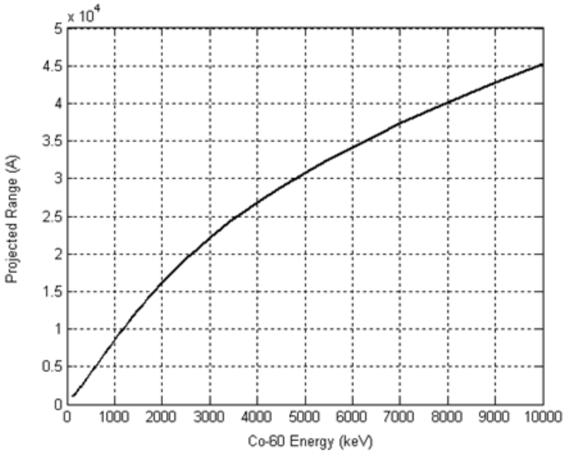


Figure 2 Projected range, R_p of ^{60}Co in silicon (Si)

The energy loss, *dE/dx* can be expressed as

$$\frac{dE}{dx} = \left.\frac{dE}{dx}\right|_n + \left.\frac{dE}{dx}\right|_e \tag{3}$$

where *n* and *e* denotes the nuclear and electronic collisions. This means that ^{60}Co ions can lose their energy in the target atom by two different mechanisms:

I. The energy transferred by the ^{60}Co ion to the target nuclei (nuclear stopping)
II. The energy transferred by the ^{60}Co ion to the target electrons (electronic stopping)

The LET function,

$$\rho m^{-1} \frac{dE}{dx} \tag{4}$$

is used to determine the total energy deposited in the semiconductor material through ionizing interactions [12, 13]. In this function, *ρm* represents the density of the material interacted, *E* is the radiation energy whereas *dx* is an elementary trajectory in the material.

Nuclear stopping involve average energy loss which results from elastic collisions by the moving Co-ion with target atoms. At the velocity of ^{60}Co ion, v_{Co} significantly lower than the Bohr's velocity of the atomic electrons, $v_o = 2.188 \times 10^8 cm/s$ the ^{60}Co ion carries its electrons and tends to be neutralized by electrons capture. The nuclear energy loss for the elastic collisions with the target nuclei at these velocities will be dominated. However, as the v_{Co} is increased, the nuclear energy loss diminished. The electronics energy loss, i.e., inelastic collisions with the target electrons will become the main interaction. The nuclear stopping and electronic stopping energy loss of ^{60}Co ion in silicon at different energy level is as shown in Table 2.

Table 2 The electronic stopping and nuclear stopping energy loss of ^{60}Co ion in silicon (Si)

Ion Energy (keV)	**dE/dx Electron (keV/ µm)**	**dE/dx Nuclear (kev/ µm)**
100	1.815E+02	9.170E+02
500	4.390E+02	5.692E+02
1,250	8.343E+02	3.450E+02
2,500	1.393E+03	2.287E+02
5,000	2.537E+03	1.416E+02
7,500	3.525E+03	1.002E+02
10,000	3.972E+03	8.464E+01

Figure 3, Figure 4 and Figure 5 show the trajectories of ^{60}Co ion in BJT at E_{Co} = 100 keV, 5 MeV and 10 MeV respectively. The red dot in the ion track represents the vacancy created by the incident ^{60}Co ion which means that an atom in the target matter is displaced from its lattice site. The red dots show that the ^{60}Co ion creates damage constantly. The other clusters of dots, namely recoil cascade, are the vacancies caused by the recoiling of target atoms.

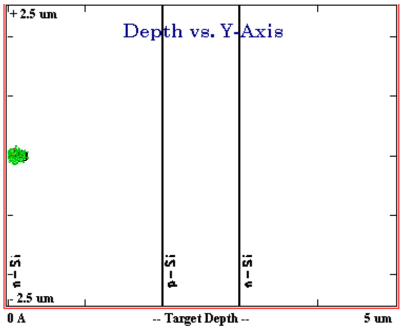


Figure 3 Plot of depth versus Y-axis at E_{Co} = 100 keV

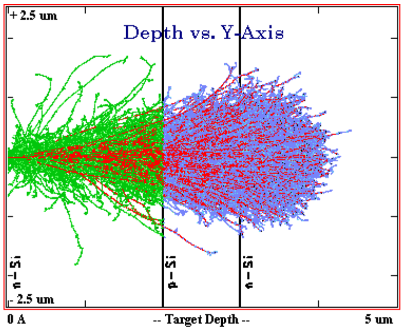


Figure 4 Plot of depth versus Y-axis at E_{Co} = 5 MeV

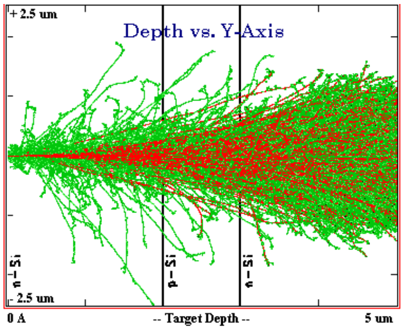


Figure 5 Plot of depth versus Y-axis at E_{Co} = 10 MeV

Displacement energy, E_{disp} is depends mainly on the direction of the momentum of the target atom. During this collision, if $E_{disp} > E_{Co}$ (energy transfer to the lattice atom of BJT), the struck atom vibrates vigorously without leaving its lattice position and appears as a localized heat source. For $E_{Co} > E_{disp}$, the struck atom is able to displace from the potential well which is a stable lattice side and move off into the lattice as a stable atom. The displaced atom produces a vacancy and occupies an interstitial site in the lattice which is known as a Frenkel-pair.

In these collisions, BJT lattice atoms which are displaced by the incident ions are known as primary knock-on atoms (PKAs). The PKAs can also in turn displace other atoms and ends up in creating a cascade of atomic collisions. This leads to the lattice disorder on the region around the ion track. The recoil energy, $E_{recoil} = E_{disp} - E_{latt}$ which is caused by the energy of E_{disp} will lost during the displacement of atom in its lattice position. Therefore, the value of E_{recoil} is higher than the value of E_{disp}. This will then continue to cause some vacancies in the lattice structure.

The lattice damage created at different energy values show significant difference on these plotting. Figure 3 shows that only a small portion of damage is induced on the surface of the BJT. From these figures, it is observed that ^{60}Co ions with a higher energy have a higher penetration depth and therefore, create a bigger damage to the lattice of the target matter. However, this damage is still depending on the R_p of ^{60}Co at that particular incidence energy.

The extraction of data for the collision events in BJT at different energy level is as shown in Table 3. It is found that if the thickness of the target material is small compared to the R_P as shown in Figure 2 at that particular E_{Co}, the energy loss in the BJT lattice will be lesser. Therefore, when the depth of target layer is reduced, the range of damage in the target material is also diminished.

Table 3 The electronic stopping and nuclear stopping energy loss of ^{60}Co ion in silicon (Si)

Incidence Energy (keV)	Damage Events		Energy Absorbed (keV/ion)
	Total vacancies	Replacement collisions	
100	2,123	170	86.9
500	7,483	596	357
1,250	12,910	1,030	664
2,500	17,370	1,415	931
5,000	20,812	1,700	1,130
7,500	22,313	1,880	1,240
10,000	20,460	1,644	1,200

The operation of the BJT is based on the charge-carrier diffusion. In an NPN BJT, electrons emitted by the n-type emitter layer will diffuse through the middle material (base) and then collected at the collector region. If the NPN BJT were at perfect condition, all the emitted electrons will be collected while some might be lost through recombination with holes in the base. Therefore, the parameter h_{fe}, which is defined as the ratio of current that reaches the collector to the amount that recombines with the base, is a vital parameter of the BJT.

Under normal operating conditions, the valence band in the semiconductor is occupied by electrons at all energy levels while only very few electrons are available in the conduction band. The forbidden energy gap between the valence and conduction bands for silicon based BJT is 1.1 eV at room temperature. The passage of the ^{60}Co ions through the BJT carries more substantial excitation energy than the thermal agitation, thus, allowing more valence electrons to be excited to the conduction band.

The high energy of the radiation leads to the production of a large number of excited atoms along its track and causes the creation of the vacancies (holes) in the valence band. This phenomenon as illustrated in Figure 6 is known as the creation of electron-hole pairs in the BJT device. The electrons in the conduction band are free to drift through the silicon material. These electrons are quite mobile and move to the most positive electrode while holes, with a rather complex transport mechanism, promote the probability of trapping.

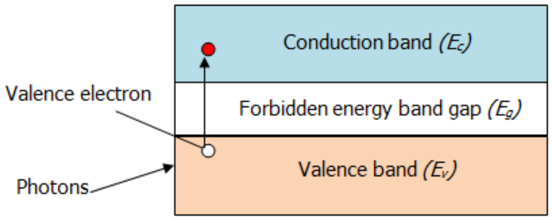


Figure 6 Excitation of electrons from valence to the conduction band

In a state of normal operating environment, the electrons are pushed from the emitter into the base region when a relatively small V_{BE} is applied. This creates a current flow across the emitter-base boundary. The electrons that get into the base region will then move swiftly towards the collector region. However, in this process flow, some of the free electrons that crossing the base might encounter a hole and recombination occur. Therefore, the increase of holes in the base region due to trapping as a result of irradiation will increase the probability of recombination and reducing the number of electrons that reaches the collector region. This research outcome hypothesis is as illustrated in Figure 7 and Figure 8.

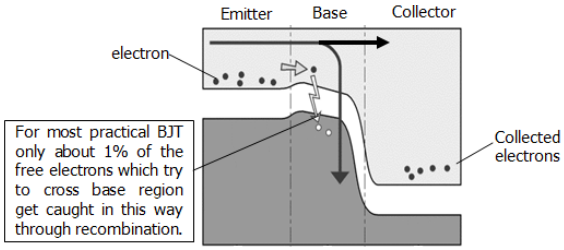


Figure 7 Normal charge flow in the BJT

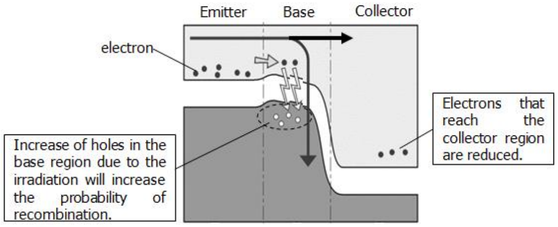


Figure 8 Research outcome hypotheses for the charge flow in BJT due the irradiation

4.0 CONCLUSION

The most significant class of damage induced by ^{60}Co ions in the BJT is the ionizing radiation effect. The second class of damage induced is the displacement damage and it is proportional to the non-ionizing energy loss. The energy deposited during irradiation results also leads to the degradation of the recombination factor. The recombination factor is an important limiting factor in the BJT's current gain. The reduction in the recombination factor is due by the increment of recombination current and this can leads to the reduction of the minority carrier life time.

5.0 FUTURE WORK AND RECOMMENDATION

Some recommendations for hardening the semiconductor devices against irradiation are as followings:

I. Increase the surface doping density in the intrinsic base. Therefore, a higher total dose is required to penetrate the surface.
II. Reduce the intrinsic surface area between the base contact and the emitter.
III. Design circuit operation for higher peak gain or current. This is due to higher operating current leads to less degradation of properties in the devices.

It would be beneficial as a future study to prepare prototypes with the "shielding" or "hardening" to understand performance of these devices at different levels and types of irradiations.

Acknowledgement

The authors are thankful to Fundamental Research Grant Scheme (FRGS) 2013, Project No.: FRG0318-SG-1/2013, with title "Evaluation on Diffusion of Charge-Carrier in Semiconductor and nanostructure Devices and its dependency on Nuclear Radiation".

References

[1] Aghara, S. K. 2003. Characterization of an In-Core Irradiator for Testing of Microelectronics in a Mixed Radiation Environment. Ph.D's Dissertation. Texas University, Austin.
[2] Wendler, E. 2009. Mechanisms of Damage Formation in Semiconductors. *Journal of Nuclear Instrument and Methods in Physics Research B*. 267(16): 2680-2689.
[3] Haider, F. A. A. and Chee, F. P. 2012. Monte Carlo Simulation of Alpha (α) Particles Penetration in Nanoscale Silicon Semiconductor Materials. *Advanced Materials Research*. 528: 237-240.
[4] Khan, F. M. and Gibbons, J. P. 2014. *Khan's the Physics of Radiation Therapy*. Lippincott Williams & Wilkins.
[5] Iliadis, C. 2008. *Nuclear Physics Of Stars*. John Wiley & Sons.
[6] Das, A. and Ferbel, T. 2003. *Introduction to Nuclear and Particle Physics*. 2nd Edition. Singapore: World Scientific Publishing Company.
[7] Haider, F. A. A. and Chee, F. P. 2012. *Monte Carlo Study of Alpha (α) Particles Transport in Nanoscale Gallium Arsenide Semiconductor Materials*. AIP Publishing. 1482(1): 559-563.
[8] Lowenthal, G. C. and Airey, P. L. 2001. *Practical Applications of Radioactivity and Nuclear Radiations*. Cambridge, United Kingdom: Cambridge University Press.
[9] Chee, F. P., Haider, F. A. A., Saafie, S. and Azali, M. 2010. Effects of Total Ionizing Dose on Bipolar Junction Transistor. *American Journal of Applied Sciences*. 7(6): 807-810.
[10] Corke, P. I. 2011. *Robotics, Vision and Control: Fundamental Algorithms in MATLAB*. New York: Springer Tracts in Advanced Robotics.
[11] Nastasi, M., Mayer, W. J. and Hirnoven, K. J. 2004. *Ion-solid Interaction Fundamentals and Applications*. UK: Cambridge University Press.
[12] Ziegler, J. F., Ziegler, M. D. and Biersack, J. P. 2010. SRIM-The Stopping and Range of Ions in Matter. *Nuclear Instruments and Methods in Physics Research*. B268: 1818-1823.
[13] Claeys, C. and Simoen, E. 2002. *Radiation Effects in Advanced Semiconductor Materials and Devices*. Verlag Berlin Heidelberg New York: Springer.