International Journal of Innovation and Applied Studies
ISSN 2028-9324 Vol. 37 No. 3 Oct. 2022, pp. 450-460

http://www.ijias.issr-journals.org/

SRIM simulation of the interaction of heavy ions ^{36}Ar, ^{78}Kr, ^{136}Xe and ^{238}U with silicon material

Idrissa Gaye[1], Stéphane Yanhdet[2], Doudou Gaye[3], Abdourahmane Diallo[1], Adam Sayoudi Bouzou[2], and Mamadou Wade[2]

[1]UFR-Sciences and Technologies, Iba Der Thiam University of Thiès, Senegal

[2]Electromechanical Engineering Department, Polytechnic School of Thiès, Senegal

[3]Electromechanical Engineering Department, Polytechnic Institute of Saint-Louis, Senegal

ABSTRACT: This paper presents the SRIM simulation investigation of energetic particles (electrons, protons, heavy ions…) irradiation. Heavy Ions used are: ^{36}Ar, ^{78}Kr, ^{136}Xe and ^{238}U. The electronic and nuclear energy losses of the incident ions and their course in the target material of silicon was calculated. We studied the stopping power or LET (Linear Energy Transfer), it makes possible to evaluate the actual path and the penetration profiles of the incident ion in the silicon target.

KEYWORDS: SRIM, electronic energy loss, nuclear energy loss, Linear Energy Transfer (LET).

1 INTRODUCTION

Semiconductor materials used on spatial or ground applications are continuously exposed to a natural and artificial radiative environment, which means that they are constantly submitted to a particles flow which transmit energy to them [1].

This contribution of energy, by charged particles (protons, electrons and heavy ions) affects in part their stability, their performance and their reliability [2].

We will then use the simulation software “SRIM 2013” to study the ionization process and damages caused [3].

SRIM 2013 is a numerical simulation software used to calculate the kinetic phenomena associated with the energy losses of charged particles (electrons, protons and heavy ions). It is a set of programs for calculating the stop and range of ion penetration into the material (up to 2 GeV / amu, amu = atomic mass unity). He uses theories of quantum mechanics to describe the ion-atom collision.

In this program, developed by Ziegler and Biersack [3], the material is supposed to be isotropic. The calculations are carried out according to a Monte-Carlo simulation, consisting of following a large number of ions individually at random from collisions. An incident particle has a rectilinear trajectory with losses of electronic energies, and then changes direction under the nuclear collisions influence. When the energy of the particle is lower than its displacement energy it stops and there is energy dissipation in the phonons form [4].

2 LINEAR ENERGY TRANSFER DETERMINATION

2.1 CALCULATION OF STOPPING POWER AND ION FLOW

The stopping power or LET (Linear Energy Transfer) of an ion in a target represents the energy loss (dE) of the ion in the target per unit length (dx). It is defined by the following relationship: [5] - [6]

$$LET = -\frac{1}{\rho} \cdot \frac{dE}{dx} \tag{1}$$

The LET is divided into two components: the electronic LET and the nuclear LET.

$$LET = LET_{électronique} + LET_{nucléaire} \tag{2}$$

We have calculated the electronic and nuclear energy losses of the incident ions and their course in the target material of silicon, taking into account a specific mass density of 2.33 g/cm^3. The ions used are: ^{36}Ar, ^{78}Kr, ^{136}Xe and ^{238}U with different energy ranges in order to clearly see the irradiation effects on the target material [7].

2.2 Electronic Energy Loss

The Electronic energy loss corresponds to the loss of energy by ionization or by excitation during the Coulomb interaction of the incident ion with the electronic procession of the atoms of the target medium.

Figure 1 below shows the profiles of electron energy loss in silicon versus irradiation energy for Argon, Krypton, Xenon and Uranium ions.

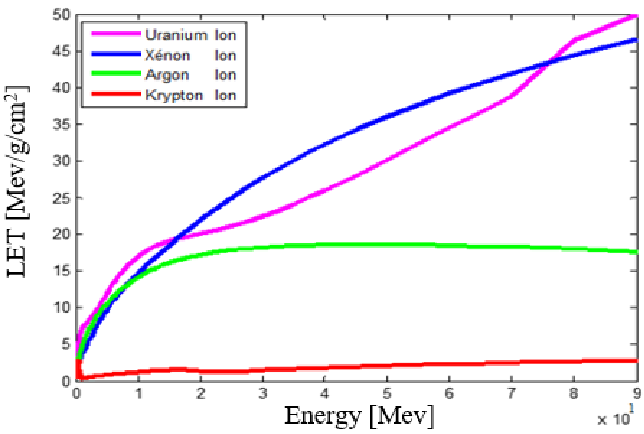

Fig. 1. Electronic energy loss by Ar, Kr, Xe and U ions in silicon depending on irradiation energy

The figure 1 shows that the electronic LET increases with the energy of incident particles. For example, the argon ion has a maximum electronic LET of about 18.65 MeV.cm^2.g^{-1} for an energy of about 45 MeV, while the uranium ion has a maximum electronic LET of about 50 MeV.cm^2.g^{-1} for an energy of about 90 MeV. This shows that heavy ions will transfer their energy only to silicon electrons. The electronic LET corresponds to the creation of electron-hole pairs by ionization during the Coulomb interaction of the incident ion with the electronic procession of atoms of the target medium. The resulting energy deposition can damage the target material [2] - [3].

2.3 Nuclear Energy Loss

The Nuclear energy loss corresponds to the loss of energy by displacement of the atoms in the medium during the interaction of the incident ion with the Coulomb field of the nucleus of the target atoms [7].

Figure 2 below shows the profiles of nuclear energy loss in silicon versus irradiation energy for Argon, Krypton, Xenon and Uranium ions.

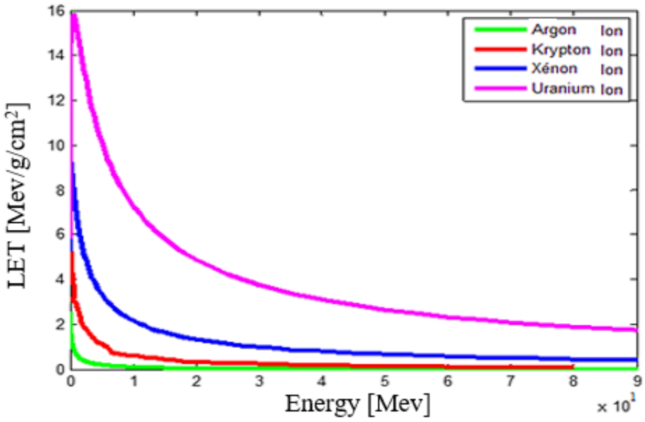

Fig. 2. Loss of nuclear energy of Ar, Kr, Xe and U ions in silicon as a function of energy

The figure 2 shows that the loss of nuclear energy is greater for ions of higher atomic number; the energy loss is very important for heavy particles. The figure 2 also shows that the loss of nuclear energy decreases with the incident ion energy; the loss of nuclear energy is less important for light particles. Thus for the same incident energy of 20 MeV for example, the uranium ion has a loss of 4,892 MeV.cm2.g-1 while the argon ion has a loss of 0.072 MeV.cm2.g-1. The figure also shows that at low energy, the loss of nuclear energy is important and then it decreases for increasing energies. This shows that light particles will transfer their energy only to the atomic nuclei of silicon. It corresponds to the loss of energy by displacement of the material atoms during the incident ion interaction with the Coulomb field of the target atoms nucleus. These direct transfers energy can also damage the target material. [6] - [9]

The following Tables 1 and 2 give respectively the electronic and nuclear LETs for heavy ions Ar, Kr, Xe and U at E = 50 Mev.

Table 1. Electronic LET values at E = 50 Mev

particules	LET ($MeV.cm^2.g^{-1}$)
Krypton	2.5
Argon	19
Uranium	30
Xénon	37

Table 2. Nuclear LET values from the projection curve

particules	LET ($MeV.cm^2.g^{-1}$)
Krypton	0.25
Argon	0.3
Uranium	3
Xénon	1

Indeed, the passage of an ion in the sensitive zone of a component, by creating a column of electron / hole pairs by ionization of the atoms of the medium, can induce a transient current which will disturb the system behavior.

3 Total Path (Or Penetration) Of The Ion In The Silicon

The total path is the distance traveled by the ion in the material until it is stopped, in other words, until it has given up its kinetic energy to the material. The stopping power makes it possible to evaluate the actual path of the incident ion in the material. Thus, the course of the ion along its trajectory in the target is defined by the following relation:

$$Range = \int_0^{E_i} \frac{1}{\left(\frac{\Delta E}{\Delta x}\right)} dE \quad (3)$$

E_i: represents the initial kinetic energy of the particle when it enters the medium [10].

3.1 Penetration Profiles Of Ar, Kr, Xe And U Ions In Silicon

The figure 3 below represents the penetration profiles as a function of the energy of the Ar, Kr, Xe and U ions in the silicon.

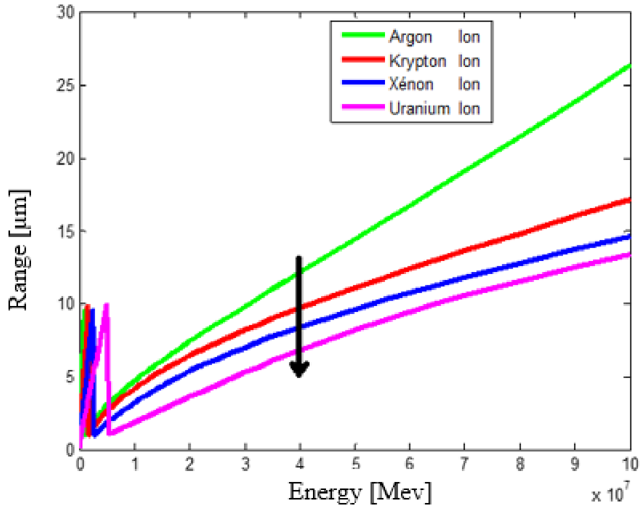

Fig. 3. Penetration profiles as a function of the energy of the Ar, Kr, Xe and U ions in the silicon

As shown in the figure, the distance traveled by a particle ion increases with its initial energy. At identical initial energies, the path decreases with the atomic number of the particle. Thus, for a given energy of 40 MeV for example, the lighter argon ion has a path of 12.13 µm and the heavier uranium ion has a path of 6.83 µm in the silicon. Silicon depends on particle velocity. Most of the energy is deposited at the end of the course.

3.2 Electronic Energy Loss Profiles As A Function Of The Penetration Of Ar, Kr, Xe And U Ions Into Silicon

Figure 4 below materializes the plot of the electronic energy loss as a function of the penetration of the Ar, Kr, Xe and U ions into the silicon.

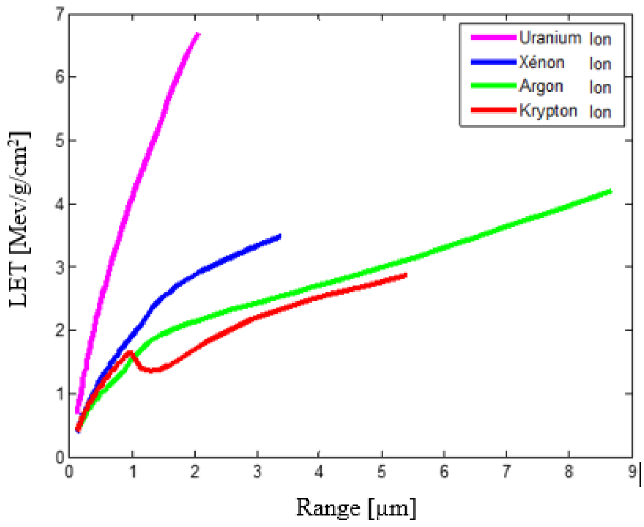

Fig. 4. TEL electronic energy loss as a function of the penetration of the Ar, Kr, Xe and U ions into the silicon

As the curve illustrates, the heavy ion of uranium has a large loss and a small path (about 6.699 KeV/ (g/cm2) and 2.061 µm). On the other hand, the light ion of argon has a small loss and a long path (about 4.215 KeV/ (g/cm2) and 8.688 µm). We also notice that the loss of electronic energy does not necessarily decrease with the path. Thus, we retain from these results that a heavy ion will deposit its energy on a small thickness of material and a light ion will deposit its energy on a greater material thickness. Variations in the LET of these particles along the path allow us to understand the effects of charge distribution and deposition. This deposition of charges through the silicon can induce a logical hazard (random, non-recurring and a malfunction at the end of the ion journey.

3.3 Nuclear Energy Loss Profiles As A Function Of The Penetration Of Ar, Kr, Xe And U Ions Into Silicon

The plot of the curves in figure 5 below represents the loss of nuclear energy as a function of the penetration of the Ar, Kr, Xe and U ions into the silicon.

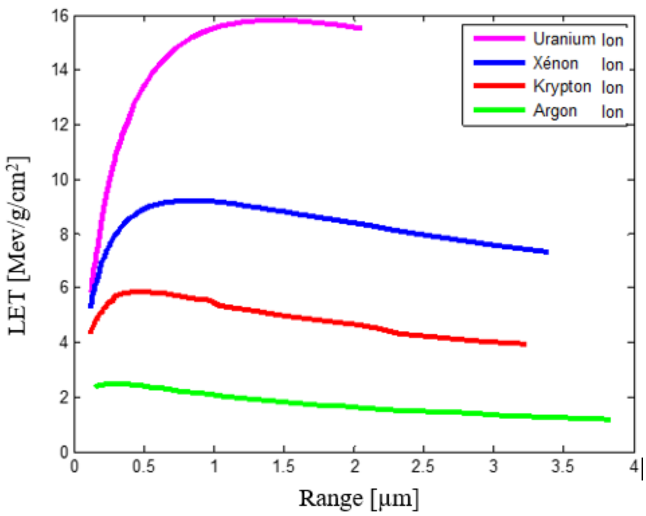

Fig. 5. Nuclear LET energy loss as a function of the penetration of the Ar, Kr, Xe and U ions into the silicon

It should be noted here that the figure materializing the variations of the energy loss with respect to the distance traveled represents the Bragg curve. We observe on these profiles a decrease in the energy loss from a maximum of deposition when the energy of the ions decreases. This maximum is called the Bragg peak.

3.4 Study Of Energy Loss Variation As A Function Of Particles Velocity

The following equation defines the relationship of energy loss as a function of velocity. [14]

$$TEL = -\frac{1}{\rho} \cdot k \cdot q^2 \cdot n \cdot \frac{Z}{v^2} \quad (4)$$

The profiles of the curves in figure 6 below materialize the variations in the energy loss of the Ar, Kr, Xe and U ions as a function of the velocity.

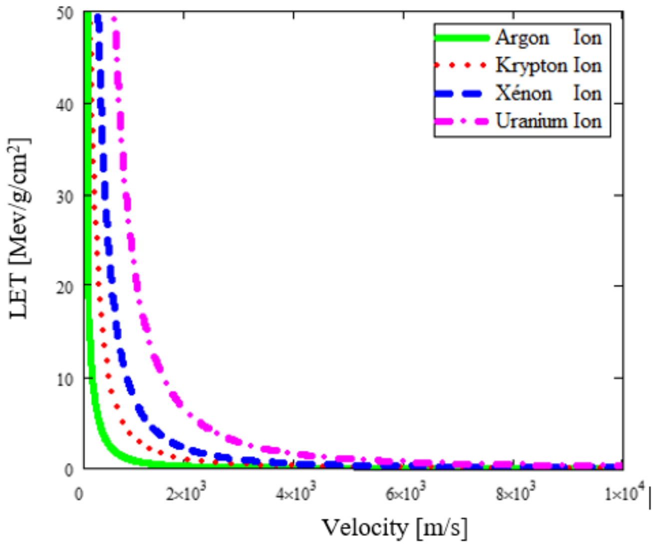

Fig. 6. Energy loss of Ar, Kr, Xe and U ions as a function of velocity

In this figure we observe a decrease in the loss of energy when the speed increases. We note here that at very high speed the Ar, Kr, Xe and U ions will in no way transfer their energy to the silicon target. Thus, the energy loss is in the low (low) speed range corresponding to collisions of the ions with the electrons of the target. The decrease in energy loss is much deeper for particles with low charges than those with high charges**.**

3.5 Study Of The Cross Section As A Function Of Energy Loss

The cross section is used to measure the sensitivity of an electronic circuit to singular effects. It is determined for several values of LET defined as the energy loss of the incident particle in silicon devices. The cross section as a function of the energy loss is defined by the following relation: [11]

$$\sigma(TEL) = \sigma_0 \cdot \left[1 - \exp\left(-\left(\frac{TEL - L_0}{\omega}\right)\right)^S\right] \quad (5)$$

3.5.1 Cross-Section Profiles As A Function Of The Energy Loss Of Ar, Kr, Xe And U Ions For Different Silicon Thickness Values

The plot of the curve profiles in figure 7 below represents the variations of the cross section as a function of the energy loss.

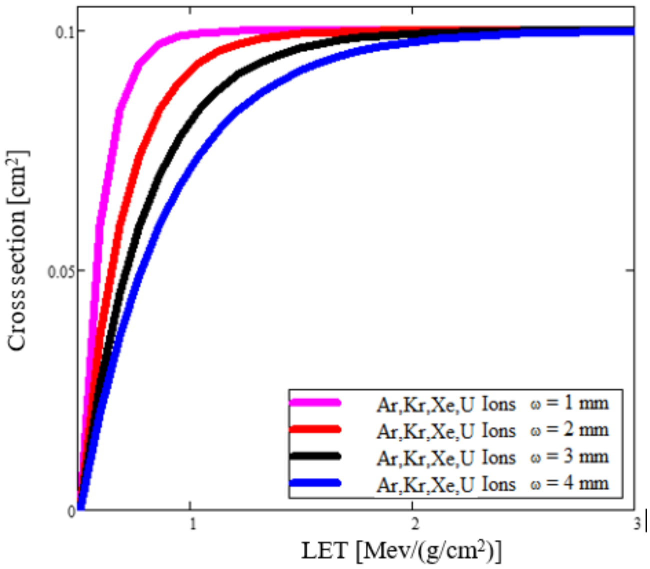

Fig. 7. Cross section of ions Ar, Kr, Xe et U in silicon as a function of LET for différents thickness values

The figure shows cross section profiles versus energy loss for different thicknesses of silicon. The graphs clearly show that the dimensions of the thickness have a significant influence on the charge deposition in the material. The lower it is, the greater the section impacted during the interaction, therefore a maximum sensitive surface. This has an impact today on microelectronic components due to the drastic reduction (increasingly advanced integration and miniaturization integrated circuits) of the size (dimension) of their circuits because it affects the reliability of integrated circuits by increasing their sensitivity to ionizing particles. TEL is used to characterize the sensitivity of a component.

3.5.2 Loss Of Energy By Radiation: Bremstahlung Phenomenon.

When a charged particle enters the field of a nucleus with kinetic energy, it experiences acceleration or deceleration. This is called braking radiation or Bremstahlung radiation [12].

3.5.3 Evaluation Of The Energy Loss According To The Incident Energy

In the figure 8, we represent the profiles of the energy loss by Bremstahlung radiation as a function of the energy for different heavy ions: Ar, Kr, Xe and U

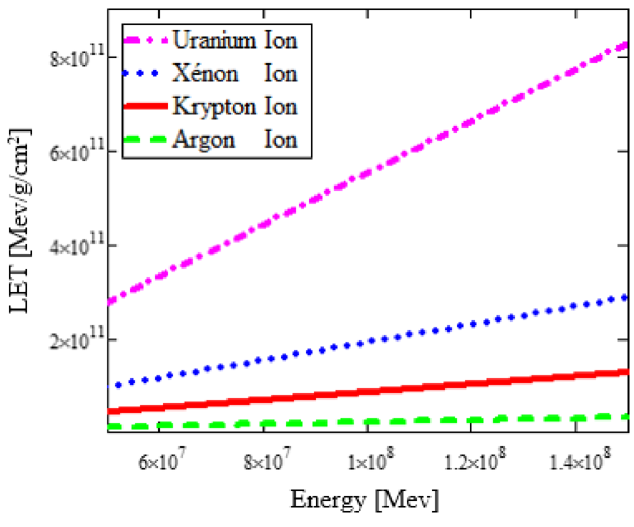

Fig. 8. Radiation LET of Ar, Kr, Xe and U ions in silicon as a function of energy

In this figure we note that the loss of energy by radiation is proportional to the energy of the incident particle. It increases with the atomic number of the incident ion.

3.5.4 Evaluation Of Electronic Energy Loss As A Function Of Thickness

The figure 9 below represents the variations of the electronic loss according to the thickness.

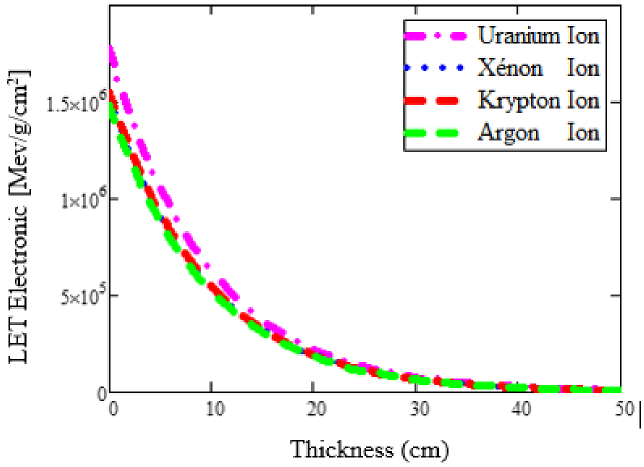

Fig. 9. Electronic LET of Ar, Kr, Xe and U ions in silicon as a function of the thickness traversed

In this figure, we observe a decrease in the energy loss following an exponential decay during the interactions of the ions 36Ar, 78Kr, 136Xe and 238U with the atomic nuclei of silicon. This is explained by a deviation in the trajectory of the charged particles causing a change in the speed of the ions which then results in an electromagnetic emission called braking radiation or Bremstahlung. The figure also shows that for the same target material (silicon) the curves representing the energy loss of the different ions studied have the same profile and that the radiation loss decreases as the material is thicker.

3.5.5 Evaluation Of Electronic Energy Loss As A Function Of Radiation Length

The profiles of the figure 10 below represent the variations of the electronic energy loss according to the radiation length.

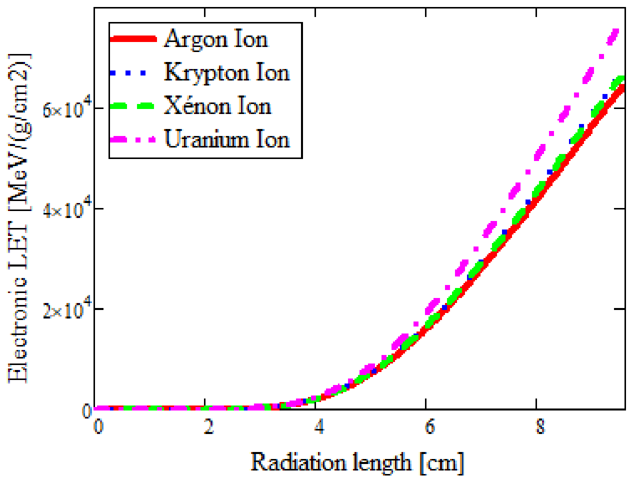

Fig. 10. Electronic LET of Ar, Kr, Xe and U ions in silicon as a function of radiation length

This figure shows that the radiation length has an effect on the loss of radiative energy. This limits the deposition of charges at the end of the path of the ion in the material.

3.5.6 Evaluation Of The Energy Deposited By The Particle As A Function Of The Thickness

The plot of the profiles in figure 11 below represents the energy deposition of the Ar, Kr, Xe and U particles as a function of the thickness

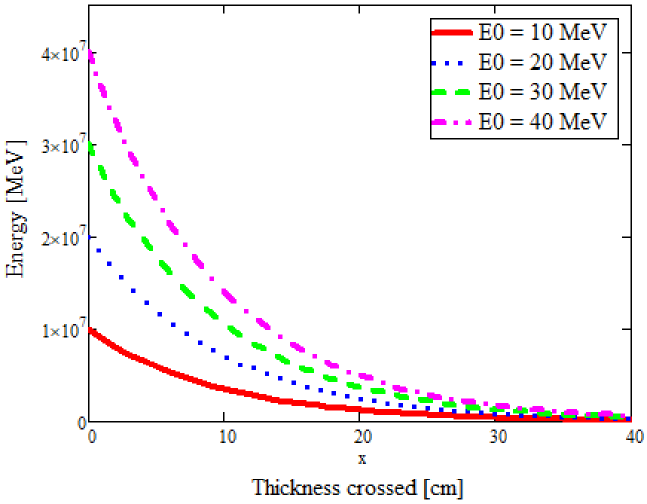

Fig. 11. Profile of the energy deposited as a function of the thickness crossed for X0 = 9.569 cm

The figure shows that the deposition of energy during the interactions of Ar, Kr, Xe and U ions with silicon depends on the thickness of the latter. Whatever the incident particle, its initial energy decreases as it penetrates the material. Thus, the thickness of the material contributed to the reduction of the stopping power by radiation.

3.5.7 Evaluation Of The Energy Deposited By The Particle As A Function Of The Length Of Radiation

The plot of the profiles in figure 12 below represents the energy deposition of the Ar, Kr, Xe and U particles as a function of the radiation length.

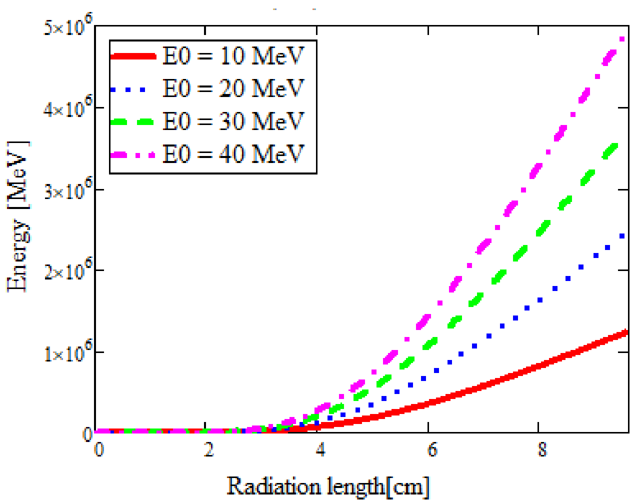

Fig. 12. Profile of energy deposited as a function of radiation length

The figure shows that the energy deposited during the interactions of Ar, Kr, Xe and U ions with silicon increases with the radiation length X0 of the material from X0 mini to X0 maxi.

3.5.8 ASSESSMENT OF NUCLEAR ENERGY LOSS AS A FUNCTION OF RADIATION LENGTH

The figure 13 below represents the loss of nuclear energy as a function of the radiation length.

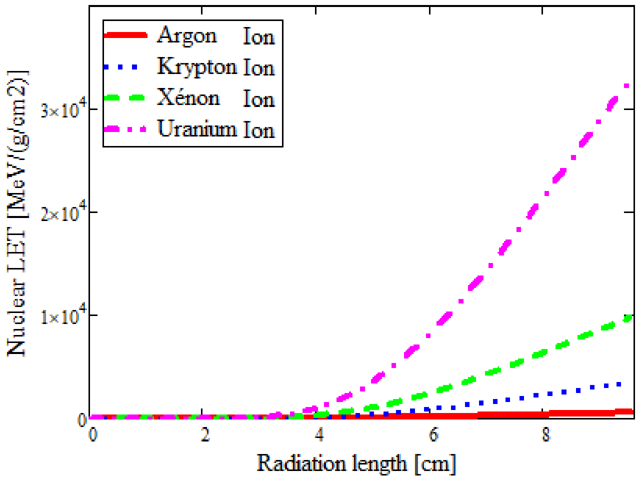

Fig. 13. Nuclear LET of Ar, Kr, Xe and U ions in silicon as a function of radiation length

In this figure we observe that the TEL appears from a certain value of the minimum X0 radiation length (about 4 cm) of the silicon material and evolves along the trajectory of the particle until the maximum X0 radiation length (9.569 cm) where it will stop.

4 CONCLUSION

The study we have just carried out has shown that the interaction of charged particles with matter leads to a loss of energy in a target material (silicon in our case) by collision and by radiation (Bremsstrahlung phenomenon). This study shows that decrease in energy loss is much deeper for particles with low charges than those with high charges, and also showed the influence of the microscopic parameters of silicon on the stopping power. The deposition of charges through the silicon can induce a transient current which will disturb the system behaviour and damage de target material.

REFERENCES

[1] Ronald L PEASE, Allan H. JOHNSTON, Joseph L. AZAREWICZ, « Radiation testing of semiconductor devices for spaces electronics", Proceding of the IEEE, vol 76, N°11, November 1988.

[2] I. GAYE, R. SAM, A.D. SERE, I.F. BARRO, M.A. OULD EL MOUJTABA, R. MANE, G. SISSOKO, « Effect of irradiation on the transient response of a silicon solar cell » International Journal of Emerging Trends and technology in Computer Science, Volume 1, Issue 3, September – October 2012, Page (s): 210 – 214.

[3] James F. Ziegler, M.D. Ziegler, J.P. Biersack « SRIM - The Stopping and Range of Ions in Matter », Nuclear Instruments and Methods in Physics Research B 268 (2010) 1818–1823.

[4] Michio YOSHIZAW, Takeshi SUGITA, Jun SAEGUSAI, Yoshihiko TANIMURA and Makoto YOSHIDA, « A Monte Carlo Program for Estimating Characteristics of Neutron Calibration Fields Using a Pelletron Accelerator », Journal of NUCLEAR SCIENCE and TECHNOLOGY, Supplement 2, p. 1240-1243 (August 2002).

[5] M.O. El- Ghossain*. Calculations of Stopping Power, and Range of Ions Radiation (Alpha Particles) Interaction with Different Materials and Human Body Parts, International Journal of Physics, 2017, Vol. 5, No. 3, 92-98.

[6] A. Javanainen, T. Malkiewicz, J. Perkowski, W. H. Trzaska, A. Virtanen, G. Berger, W. Hajdas, R. Harboe-Sørensen, H. Kettunen, V. Lyapin, M. Mutterer, A. Pirojenko, I. Riihimäki, T. Sajavaara, G. Tyurin, and H. J. Whitlow, « Linear Energy Transfer of Heavy Ions in Silicon». IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 54, NO. 4, AUGUST 2007.

[7] Juraj Hanžek, Pavo Dubˇcek*, Stjepko Fazinı́c, Kristina Tomı́c Luketı́c and Marko Karlušic *. High-Energy Heavy Ion Irradiation of Al2O3, MgO and CaF2, Materials 2022, 15, 2110. https://doi.org/10.3390/ma15062110.

[8] J. J. GROB, A. GROB, A. PAPE, P. SIFFERT. Energy loss of heavy ions in nuclear collisions in silicon. Centre de Recherches Nucléaires et Université Louis Pasteur, 67037 STRASBOURG CEDEX - FRANCE.

[9] S. MARTINIE, T. SAAD-SAOUD, S. MOINDJIE, D. MUNTEANU, J.L. AUTRAN. « Behavioral modeling of SRIM tables for numerical simulation", Elsevier journal, Volume 322,1er mars 2014, pages 2-6.

[10] Haider F. Abdul Amir and Fuei Pien Chee, Member IACSIT, « Characterization of Proton Irradiation Effect in Semiconductor Material", International Journal of Applied Physics and Mathematics, Vol. 3, No. 5, September 2013, Pages: 341-344.

[11] Nestor R. Arista, « Energy loss of ions in solids: Non- linear calculations for slow and swift ions", Nuclear Instruments and Methods in Physics Research B 195 (2002) 91–105.

[12] O Embréus1, A Stahl and T Fülöp, « Effect of bremsstrahlung radiation emission on fast electrons in plasmas", New J. Phys. 18 (2016) 093023, doi: 10.1088/1367-2630/18/9/093023.