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The basics of radiation damage in crystalline silicon networks by NIEL

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ABSTRACT

Basically, radiation can cause two effects on materials: ionization and non-ionization. This work presented the theory involved in defects caused by non-ionization, known as NIEL, with a focus on silicon materials. When energy is transferred directly to the atoms in the crystalline lattice, it can either be dissipated in the form of vibrations or be large enough to pull atoms out of that lattice. This weakens the lattice, causing measurement errors that can lead to permanent damage. This study is extremely important because silicon materials are used in radiation detectors. These detectors cannot return false measurements, especially in dangerous situations, such as in nuclear reactor monitoring. After presenting the theory involved, examples are shown. Failures of up to 30% were found by the researchers.

Key words: Non-ionizing energy loss, NIEL, radiation damage, diodes, silicon, nuclear reactor monitoring, radiation detection

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1. INTRODUCTION

The interaction of radiation with matter causes damage to materials. This damage can be permanent or temporary and results in a wide variety of chemical and physical effects. Depending on the quantity, type of radiation and energy, the effects of radiation can, for example, degrade the performance of devices (figure 1), kill cells or weaken materials.

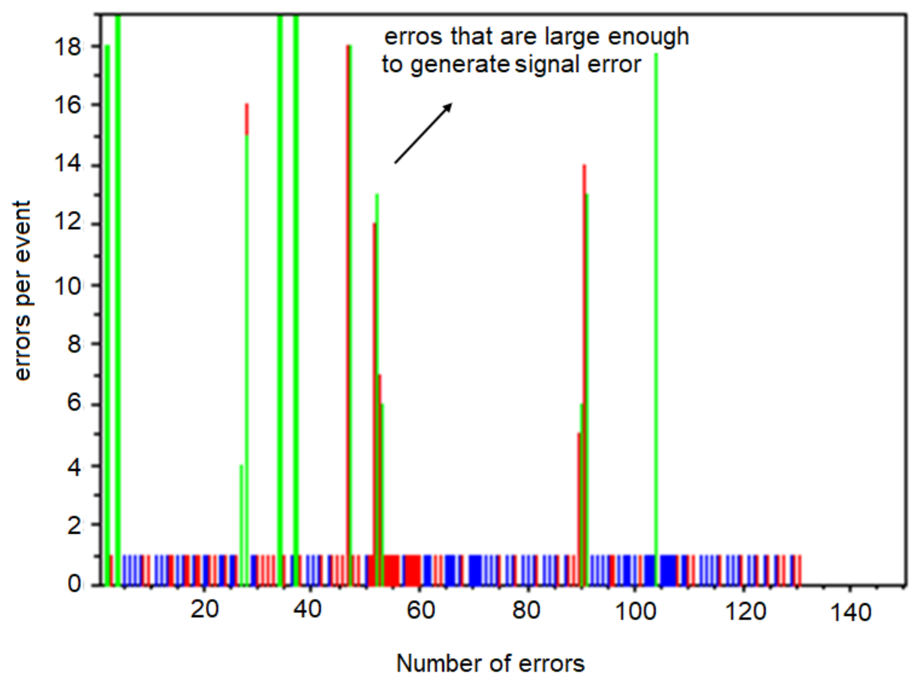

Figure 1: Example of damage caused by radiation in silicon detectors. The false signal was caused by a single event.
Source: [1].

It is extremely important to study these effects. The materials used in shielding, construction of nuclear reactors, solar panels subjected to space radiation (at the International Space Station, for example), and radiation detection needs to be reliable. Predicting the rate of degradation of these materials is directly linked to safety and good practices in the use of radiation. Most research in the field is done for devices containing silicon plates. Silicon is the active material in some radiation detectors (such as semiconductors) and the base material for electronic devices used in the manufacture of electronic circuits. Being able to rely on the readings of sensors and detectors containing silicon is crucial to ensure operating limits.

There are several forms of interaction between radiation and matter. But basically, it can:

- To suffer a change of direction due to electric fields (Rayleigh and Thomson scattering);
- Interact with the electronsphere (photoelectric effect, Compton effect and production of pairs / triplets);
- Interact with the nucleus of the atom (nuclear reactions);
- Interact with the atom as a whole [2, 3].

Non-ionizing energy loss (NIEL) processes are interactions in which the energy transferred by the incident radiation does not result in ionization, but has an effect on the crystalline network of the material. Direct collisions may be sufficient to remove an atom from the crystalline lattice (when this is a primary atom, it is abbreviated to pka) or create a transfer not strong enough to move the atom from its location in the lattice, dissipating energy in the vibrations of the lattice. network (phonons).

The objective of this work is to present the physical concepts of NIEL. At the end of the work, 3 examples are presented.

2. THE NIEL

Figure 2 shows what happens when an atom is removed from the crystalline network of a solid material. Because of vacancy, the crystalline structure rearranges, causing tense regions, weakening the network.

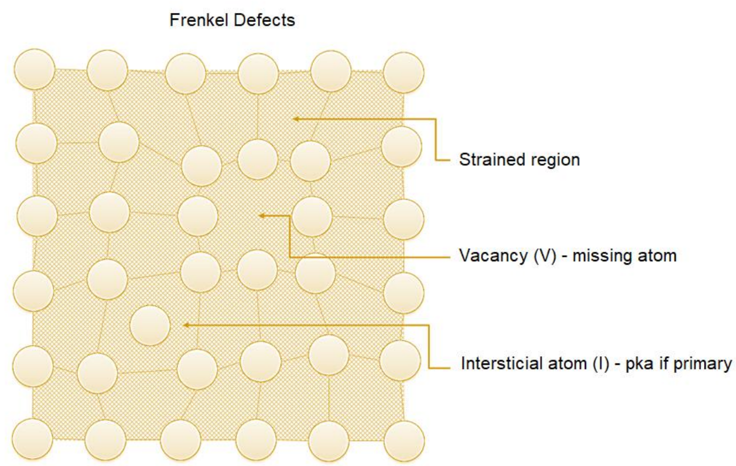

Figure 2: Scheme of the results of an atom removed from the crystalline network.
Source: [4].

The deposition of energy by non-ionization processes is much less than by ionization. Figure 3 shows the contribution fractions of atomic displacement damage (NIEL) and ionization damage by the fractions of kinetic energy of the recoil silicon [1, 5].

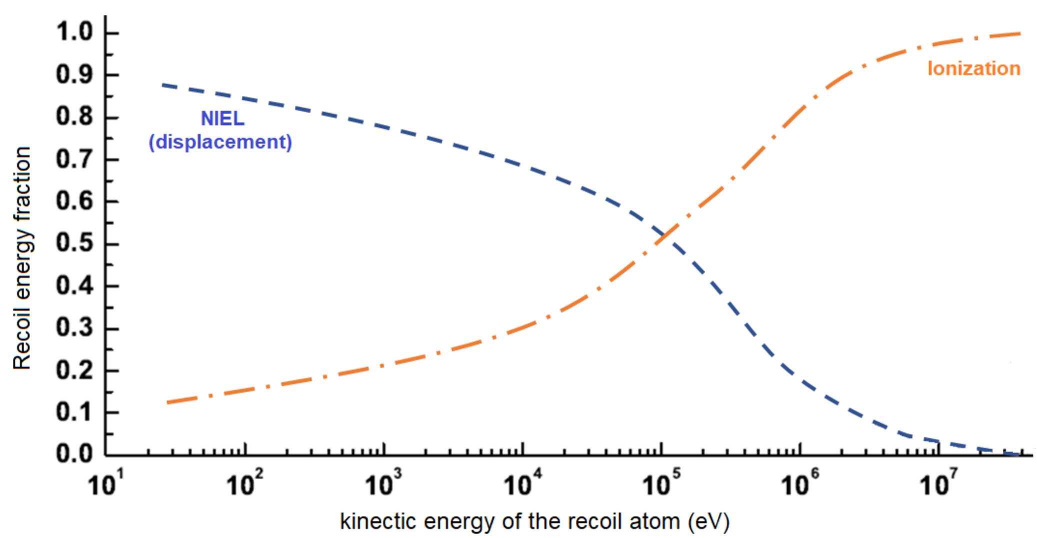

Figure 3: Fractions of kinetic energy of the recoil silicon deposited in processes that produce defects (blue line) and ionization losses (orange line)
Source: [4].

Defects induced by the interaction of radiation with semiconductors are primary point defects: voids or vacancies (V) and interstitial (I). Cluster defects are generated when the incident particle, like a fast neutron, transfers enough energy to the receding atoms to allow large cascades of displacement. This change observed in the conductivity of the semiconductor and is associated with the formation of clusters of defects [1, 5]. If the energy transferred is high enough, the semiconductor can be damaged to the point of permanent damage. The rate at which the semiconductor properties are degraded is calculated as (eq. 1):

$$\frac{1}{\tau_{irr}} = \frac{1}{\tau} - \frac{\emptyset_i}{k_{\tau,i}} \tag{1}$$

τ_{irr} is the time of recombination after radiation, τ is the recombination time before radiation, $\emptyset_i$ is the fluency of the particles and $k_{\tau,i}$ is the coefficient damage for each lost recombination. τ_{irr} depends on the material, concentration of the dopant and the “i” type of particle and, consequently, on the “i” energy [1, 5].

Figure 4 shows an example of cascade displacements simulated by a recoil atom (atom removed from the network) after interaction with an incident neutron of 50 keV kinetic energy. Some energetic collisions produce other energetic recoil atoms interspersed with many other low-energy transfers. Thus, cascading displacements result in clusters (terminals) of defects. The thermal energy allows some defects to migrate through the crystal and, eventually, be annihilated by the recombination of the V-I pairs or create stable defects in association with other impurities or defects already present (or induced by radiation). For example, a recoil atom with kinetic energy of 50 keV can generate clusters with sub-clusters of defects that extend up to about 100-800 Å [1].

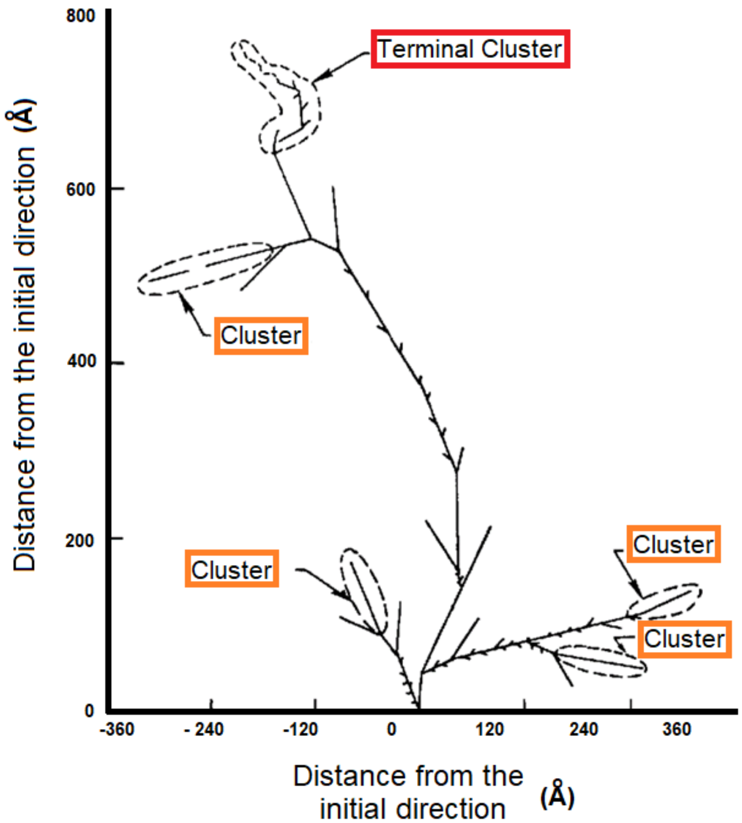

Figure 4: Simulation of cascading displacements generated by a recoil atom after interaction with an incident neutron kinetic energy of 50 keV
Source: [1, 4].

For example, low resistivity p-n diodes can gradually change their internal structure with an increase in the flow of fast neutrons. Non-irradiated diodes with ohmic contact (n+) can acquire an almost p - i - n structure after irradiation [5].

3. THE DAMAGE

Non-ionization processes produce displacement damage that can lead to clusters of defects. The recoil atoms are removed from their initial network position and moved to interstitial positions. However, if the recoil energy of the primary atom is greater than the limit for atomic displacement, that atom can produce the displacement of another atom. While the recoil energy is above the displacement threshold, the process will produce cascading V-I [5].

The effects of mass damage produced by energetic particles have been shown to be proportional to the cross section of displacement damage equivalent to the loss of non-ionizing energy. The proportionality between the NIEL value and the resulting damage effects is called the NIEL escalation hypothesis [5].

Subject to fluency, the main effects on the operation of silicon detectors are: increased leakage current, increase in the total depletion polarization voltage to be applied to the detector, and decrease in charge collection efficiency (CCE). The damaged regions created by the radiation dose in the silicon volume act as electrically active defects with deep levels in the prohibited band in the silicon [5].

The generation of these additional traps shortens the life of the charge carriers and increases the reverse current. For fluencies of the order of 10^{14} particles.cm^{-2} the reverse current can reach values in the range of several tens of μ/ cm^{-2}. However, the strong temperature dependence of the reverse current allows it to be minimized by operating the detectors at a moderately low temperature (in a range -5 to -10 °C, which is not always practical and limits the use of the equipment). Another example is the recombination and the breakdown of the recombination, generating even more leakage current and causing the total depolarization of the equipment. Often, a pause period of 2 weeks for 50 % of the recombination to occur and the equipment can be reused [5]. Eventually, this time will increase to the point that the device is no longer possible to use.

3.1 NIEL and displacement damage

Displacements occur when the primary interaction results in the removal of an atom from the network (recoil atom). So-called Frenkel pairs are then formed. A Frenkel defect is a pair of point defects close enough to exhibit an interaction: vacancy (V) and an atom in an interstitial position (I). For collisions strong enough to allow large transfers of energy, the PKA (primary knock-on atom) can collide with other atoms in the network, creating more empty spaces and interstitial atoms. In thermal equilibrium, the receding atoms will be located in interstitial positions, unless some of them recombine with vacancies. Some of these point defects are isolated, but for recoil energies much greater than the displacement threshold energy E_d, cascade displacements will occur in a spaced group of defects (cluster of defects) within a small spatial region (or even some small regions) [5].

In radiation-induced defects, E_d it is several times greater than the energy required for the adiabatic displacement of atoms in the network to interstitial positions. E_d it depends on the direction of the recoil and, for silicon, it is about 13–33 eV. In most calculations, particularly for neutrons, an average value of 25 eV is assumed [5].

Most predictions of neutron energy dependence on silicon semiconductor devices were based on the amount of non-ionizing energy deposited. In the literature, the damage effect due to neutron-induced initial and cascade displacements is expressed by the damage function (also called the kerma displacement function) D (E) in units of $MeV.cm^2$ or MeV.mb [1, 5]. The damage function, which is responsible for the cross-section of the neutron-silicon scattering and for the energy released in the creation of displacements, is given by (eq. 2):

$$D(E) = \sum_k \sigma_k(E) \int f_k\,(E,\,E_R).\,P_k(E_R)dE_R \tag{2}$$

where E is the incident neutron energy, σ_k (E) is the area section for the k-th reaction, f_k (E,E_R) dE_R is the probability that a recoil atom is generated with kinetic energy between E_R and $E_R + dE_R$, and P_k (E_R) is the partition energy for the recoil core. This last term is the part of the recoil energy deposited in displacements calculated in the structure of Lindhard's partition theory [5].

From eq. 2, the density of deposited energy across atomic displacements by neutrons characterized by the spectral fluency of neutrons ϕ (E) in n.cm^{-2}.Mev^{-1} , is given by (eq. 3):

$$E_{dis} = n_{Si} \int_{E_{min}}^{E_{max}} D(E)\, \emptyset(E)\, dE \tag{3}$$

where $n_{Si} = \rho_{Si} N/A_{Si}$ is the number of atoms per cm^3 in silicon, ρ_{Si} and the A_{Si} are the density and atomic weight of the silicon medium, respectively; N is the Avogadro's Number and E_{min} is the minimum energy of neutrons to induce displacement damage [5].

The concentration of Frenkel defects per cm^3, can be calculated using the modified Kinchin-Pease formula and considers the limit energy for displacement, E_d (eq. 4):

$$[FP] \sim \frac{E_{dis}}{2.5\, E_d} \tag{4}$$

When there is no nuclear transformation, the dose absorbed in devices (of silicon) is responsible for the energy deposited by the energy loss processes of primary particles. For nuclear reactor fast neutrons, the dose contribution (D^{NIEL} in Gy) is [1] (eq. 5):

$$\mathrm{D}^{\mathrm{NIEL}} = \frac{\mathrm{E_{dis}}}{1.45\ 10^{10}} \tag{5}$$

3.2 Interactions with different Radiations

The energy required to remove one of the atoms from the silicon network depends on the form of radiation. As each type behaves differently, each has a different equation that represents the necessary conditions of the NIEL [1, 5]. They are shown in figures 5 and 6:

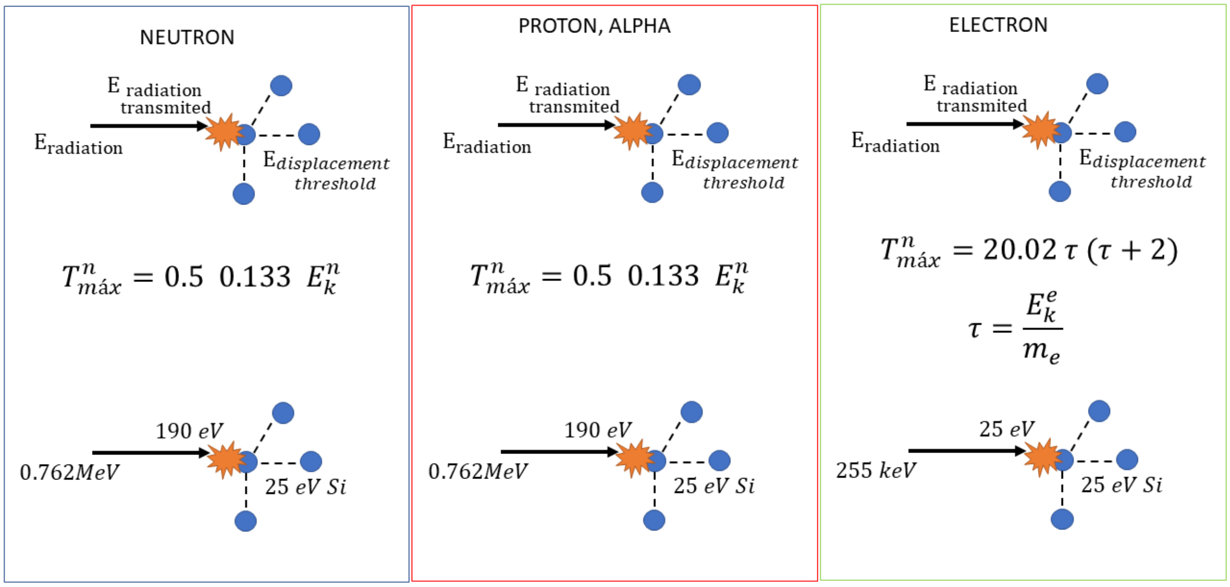

Figure 5: Equation of energy and energy transfer required for different forms of radiation for NIEL. Caption: τ = the kinetic energy of the electron in units of its resting mass, $T^n_{máx}$ = maximum˙ energy transferred to the type n radiation, E^n_k = incident kinetic energy for type of radiation n.

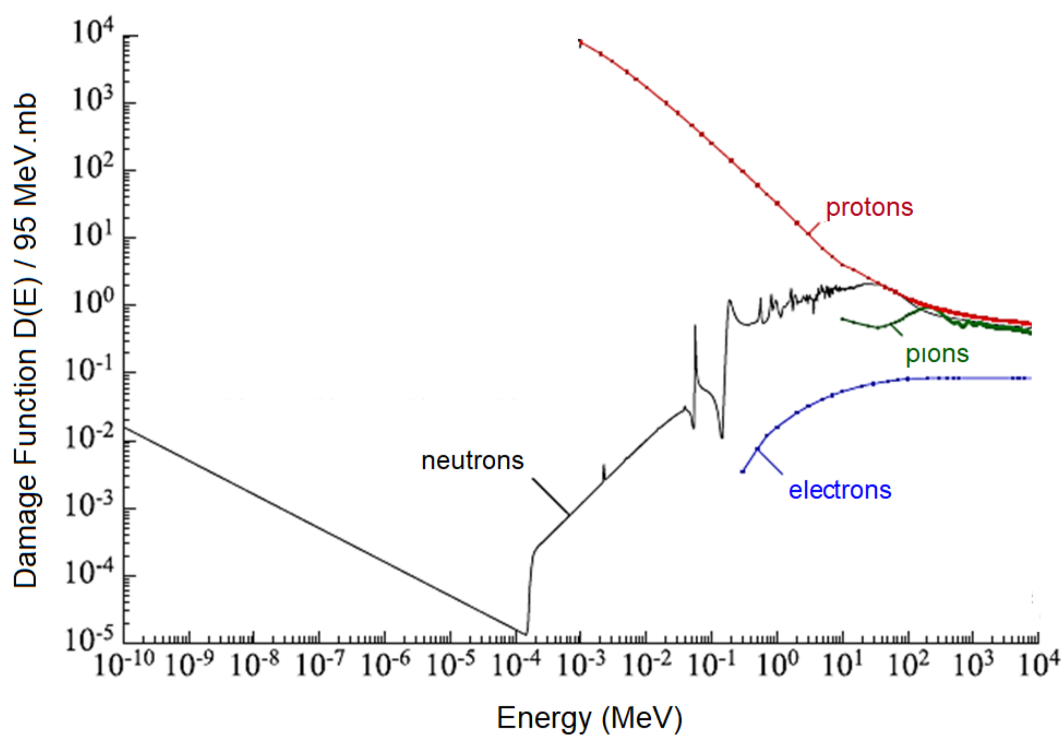

Figure 6: Energy displacement x particle energy graph for different radiation Source: [4, 6].

For example, for electrons it is necessary that the incident radiation provides 255 keV of energy for the silicon atom in the network to be displaced. For protons, it is necessary for the incident radiation to supply 762 MeV of energy to the silicon atom of the network to be displaced [1].

4. EXAMPLES

AH Johnson of the Jet Propulsion Laboratory, a NASA partner, published an extensive study of the effects of space radiation on the equipment of the International Space Station. According to the author, atom displacement damage (NIEL) is the main cause of damage in optoelectronic devices, integrated circuits, and optical emitters. For example, when the bipolar device is irradiated with protons, the circuit degrades and the device fails catastrophically at levels of equivalent total dose between 18 and 35 Gy. In optoelectronics, about 50 % of the light output was lost with 3 Gy radiation dose. For reference, in space there is an average dose of 3 Gy, which can reach 40 Gy during solar events [7] (The dose of 0.5 Gy of the whole body can kill a human being if he does not receive any medical treatment).

Onoda et. al. investigated the load collection characteristics of damaged samples. The damage was induced by ion beam and evaluated by measuring transient currents induced by heavy ions. The results of this study suggest that ion-induced charge degradation can be predicted for any kind of ion and energy using the concept of non-ionizing energy loss (NIEL) and dose of displacement damage. Heavy oxygen and gold ions were used (from a Tandem accelerator and an AVF cyclotron). The material used were pin silicon photodiodes with 450 μm in diameter. The damage factor was $2.2.10^{-14}$ g / MeV. This means that for each MeV of energy, $2.2.10^{-14}$ g of material is damaged. This was enough to reduce the amount of collected charge by 20% [8].

Hillemanns et. al. reported the degradation of a detector used in the Large Hadron Collider (LHC, Large Hadron Collider, Europe). The material used were 15x30 mm pin silicon photodiodes. A particle flow of 1.10^{13} 1 MeV n_{eq} cm^{-2} in ^{55}Fe was used. Results showed a 20% decrease in measuring capacity [9].

Due to their cost-effectiveness, Si pin diodes are currently used in several applications, including those that require operation in high radiation environments. For this reason, Jakšić et. al. [10] studied the damage to the 25 mm^2 p-i-n type diodes with a 4.5MeV proton beam. The damage caused by NIEL reduced the amount of cargo collected by 30%.

The true cost of NIEL is difficult to estimate. It might range from diminished life expectancy of the device to unfeasibility of the project. NIEL have to be calculated and its effects might subtract years in the life expectancy of the device. For example, Akkerman et. al. [11] found that the estimation of the V-I recombination rates are in contradiction with a computer simulation of the evolution of the damage region. This suggests that the NIEL model is reliable to predict only early stages of damage in high radiation environments. Laboratory damage measurements are necessary to ensure reliability of the device.

In low radioactive environments, radiation damage by NIEL can diminish, for example, the thermoelectric conversion efficiency in nuclear batteries. In Wang et. al. [12] commercially available bismuth telluride materials showed significant changes in individual properties. N-type materials electrical properties and p-type materials thermal conductivity were affected by irradiation-induced defects. This might result in radiation levels restriction for the device usability. In betavoltaic devices, protection layer of the p-i-n diode is not possible, due to shielding of the desirable beta particles.

5. CONCLUSION

Basically, radiation can cause two effects on materials: caused by ionization and caused without ionization. This work presented the theory involved in defects caused by non-ionization, known as NIEL, with a focus on silicon materials. When energy is transferred directly to the atoms in the crystalline network, it can either be dissipated in the form of vibrations or be large enough to pull atoms out of that network. This weakens the network, causing measurement errors that can lead to permanent damage.

This study is extremely important because silicon materials are used in radiation detectors. These detectors cannot return false measurements, especially in dangerous situations, such as when monitoring nuclear reactor with electric sensors. Research in this area continues to be carried out mainly in research groups linked to the LHC in Europe and in the aerospace area. With the advent of nuclear batteries, the area is expected to grow in the coming years.

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