Transient and Post-irradiation Response of Optoelectronic Devices to Ionizing Radiation

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Abstract. Space and ground level electronic equipment with semiconductor devices are subjected to the deleterious effects by radiation. This paper is attempted to present the transient and post-irradiation response of optoelectronic devices to gamma (γ) rays utilizing cobalt-60. In situ measurements were made on the devices under test (DUTs) up to a total dose of 60 krad followed by a post-irradiation not in-flux test for eight hours. Current transfer ratio (CTR) with is the vital merit of the optoelectronic system is found to decrease remarkably with the absorbed dose. This degradation is induced by the interaction of the energetic photons from gamma rays via two main mechanisms. The dominant effect is the mechanism by ionization while the secondary is by displacement. This radiation effect is found to arouse either a permanent or temporarily damage in the DUTs depending on their current drives and also the Total Ionizing Dose (TID) absorbed. The TID effects by gamma rays are cumulative and gradually take place throughout the lifecycle of the devices exposed to radiation. The full damage cascade phenomenon in the DUTs is calculated via the simulation.

1. Introduction

Studies for introduction of atoms into a solid substrate by bombardment of the solid with ions in the electron-volt (eV) to mega-electron-volt (MeV) energy range have always received great interest [1]. These interests have been stimulated by the feasibilities of synthesizing novel materials with potential applications in the semiconductor, mineral processing and metallurgy, corrosion and optical fields. Moreover, operating environment of the equipment and devices for the technologies on weather forecasting, remote sensing, global navigating position, satellite television and data broadcasting, telecommunication system as well as our surveillance and army based national security technologies are far from stable and not without interference [2, 3]. The physical properties for a particular solid substrate are always sensitive to the presence of a trace amount of foreign atoms. Mechanical, electrical, optical, magnetic and superconducting properties are all affected and sometimes may even be dominated by the existence of such foreign atoms [4, 5].

Gamma rays are photons which are electromagnetic radiation with zero mass, zero charge, and travel with the speed of light, c. Since these photons are electrically neutral, they do not steadily lose energy via collisonic interactions with atomic electrons as what happened in charged particles. Instead, they travel some considerable distance before undergoing an interaction. Penetration of
gamma rays can be governed statistically via interaction probabilities, per unit distance travelled, which depend on energy and material. This probability is known as the linear attenuation coefficient and has the dimensions of inverse length (e.g. cm⁻¹). Gamma rays have higher penetration intensity compared to the charged particles of similar energy. Gamma rays can interact with matters primarily in three processes. These are the photoelectric effect, Compton scattering, and pair production [6]. Therefore, the semiconductor device that is exposed to an ionizing radiation environment typically endures degradation in one or more of its performance parameters.

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) [7]. 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 systems and nuclear energy loss through nuclear collisions with the target atoms. The incident ions will finally come to rest at a certain depth, z.

This paper presents the analytical and numerical changes in optoelectronic devices as a result of gamma radiation. Since the previous study which was modelled on the optoelectronic material had been presented [8, 9] and therefore this paper will further the simulation study to damage extents at different energy level in the structure of the device.

2. Research Methodology

Basically, the research work was divided into two main parts; the first part was the test of gamma radiation effects on the optoelectronic devices while the second part was the Monte Carlo simulation of the resulting mechanism in the model of the DUTs.

2.1. Specialized Devices

Optoelectronic devices consisting of a Plastic IRLED (QEE113) coupled to a Plastic Silicon Infrared Phototransistor (QSE113) is being studied in this research. The QEE113 is a 940 NM GaAs LED, encapsulated in a medium wide angle and clear epoxy plastic side looker package. The QSE113, however, is an NPN silicon phototransistor encapsulated in a wide angle, infrared transparent and black plastic side looker package.

Optoelectronic devices are being studied as they play an important role in optical satellite telecommunications and sensing technology. They are widely used especially in providing electrical isolation between circuits such as a sub-system to sub-system interfaces for space light designing’s. These photonics systems are ideal for applications in space system due to their high bandwidth and speed of operation, the immunity to electromagnetic interference, low power consumption and cost, yet, for high reliability. Thus, the understanding of the processes which leads to device failure is crucial in order to meet the radiation hardness requirements.

For the IRLED and phototransistor, two of them are electrically isolated. The phototransistor is a photodetector which is capable of converting the received infrared light into current or voltage. Therefore, the current change in the phototransistor is depending on the forward current, I_f, of the IRLED. In this study, I_f is set at 25, 50, 75 and 100 mA. The I_f of the IRLED can be raised up to 1000 mA, yet, for ideal performance of this device, the I_f range is 10 to 100 mA.

2.2. Radiation Exposure

The radiation testing on the electronic devices consist of multi-parameter test with different exposure levels. Ambient temperature throughout the test was 25±3°C. Before the irradiation process, a control test of 72 hours is performed on the DUTs. This is known as the pre-irradiation testing. Only devices which are within the specific working range and the testing results which reveal that they are within the standard deviation of 2 sigma are submitted for radiation testing. The radiation procedure was referred from the Military Standard (MIL-STD) 883G Method 1019.7, Ionizing Radiation (Total Dose) Test Procedure [10].
The output collecting current, $I_C$ of the phototransistor is measured for bias forward current ($I_F$) of 25 mA, 50 mA, 75 mA and 100 mA. The schematic of experimental setup for the optoelectronic device is as shown in Figure 1.

The input voltage of the particular device could be changed from a distance of approximately 15 m in a control room during irradiation and the effect could be observed directly using in-situ method. The information and status of the device under test (DUT) will be transmitted through the driver circuit based on an ADC circuit into the PC. The temperature dependence of the charge deposition in the sampling device would be monitored with an electronic thermometer using LM35 precision centigrade temperature sensor. All the data presented to the computer will then be processed and analyzed by the MATLAB program.

![Figure 1. Circuit of experimental setup for the optoelectronic device.](image)

Exposure on the DUTs is utilizing the cobalt-60 ($^{60}$Co) gamma rays from RAYMINTEX Plant, Malaysian Nuclear Agency. Gamma rays are substantial portion of the photon output of a nuclear detonation [11]. Fissions occurring in the nuclear detonation will provide prompt gamma rays and X-rays that are expelled from the burst as part of the menagerie of particles and radiation energy. Gamma rays are also emitted from radioactive fission fragment components of the bomb fuel debris, as well as from the neutron activated atomic nuclei of weapon [12]. The nature and behavior of gamma rays are in marked contrast to those of neutrons. They have zero rest mass which means that their existence ceases by annihilation when they are brought to rest, as when absorbed by matter [13].

The DUTs are exposure up to a total dose 60 krad. This value is chosen with reference to the NASA report from Poivey [14]. In this research paper, a more accurate estimation of the radiation level using 3D Monte Carlo code is utilized to calculate the total dose level received by the part at geostationary orbit. According to the analysis, the highest 15 years dose level simulated from Monte Carlo code is 24.0 krad whereas those simulated from sectorial analysis- shell sphere/norm model and solid sphere/slant model is 28.5 krad and 18.6 krad respectively. From this data, the total dose of 60 krad is sufficient to cater to a most stringent condition in the proposed space environment. The dose rate at the selected point could be determined based on Equation 1.

$$DoseRate (rad/s) = \frac{DoseAbsorbed (rad)}{ExposureTime (s)}$$  \hspace{1cm} (1)

Since the dose rate at that particular point is known, the exposure time to radiate the DUT up to a total absorbed dose of 60 krad can be calculated. This special configuration and positioning of the coordinated table mode irradiation controlled the distance between the DUT and $^{60}$Co sources. This allows equal exposure of radiation at a pre-determined constant dose rate. The dose rate of the activity shows a variation at different time due to the half-life of $^{60}$Co. However, this variation is not significant for tests which were conducted at a same period.

2.3. Monte Carlo Simulation

Monte Carlo method is a class of computational algorithms that rely on repeated random sampling and probability statistics to compute their results [15]. 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 [16].

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 to the loss of energy: damage to 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 [17].

This paper will discuss and analyze the interaction between $^{60}$Co ions with the optoelectronic device at different energy level using the SRIM-TRIM. 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.

By the simulation of the 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.

3. Results and Discussions

Current Transfer Ratio, $CTR$ is defined as the ratio of $I_C$ to $I_F$. The rate of change in the current transfer ratio, $\frac{CTR}{CTR_0}$ on the optoelectronic device tested is being monitored and recorded. Figure 2 shows the relationship between $\frac{CTR}{CTR_0}$ of optoelectronic devices with the total dose absorbed. $CTR_0$ is the reading at pre-irradiation whereas $CTR_f$ is the reading after being exposed to irradiation.

Drop off for the $I_C$ parameter results in a linearly decreasing $CTR$ across the gamma radiation period for different forward biased current applied at a step rate of 25 mA. From this graph, it is illustrated that a higher operating $I_F$ has led to lesser depletion in the $CTR$ of the optoelectronic devices.

![Figure 2](image)

$\frac{CTR}{CTR_0}$ during irradiation for different bias $I_F$

The line graph in Figure 3 indicates the $\frac{CTR}{CTR_0}$ of optoelectronic devices during the post-irradiation. After the removal of the radiation, the $CTR$ recovers gradually for different forward biased current applied at a step rate of 25 mA. In addition, it is observed that the greater percentage of
increase in CTR occurs at a lower bias $I_F$. The percentage of recovery at post-irradiation is lesser at $I_F = 100$ mA because the high $I_F$ yields a saturation condition to the operating system.

![Figure 3](image.png)

Figure 3. $\frac{CTR}{CTR_0}$ at post-irradiation for different bias $I_F$.

When a flux of energetic $^{60}$Co ion traverses the target of thickness $dx$ and containing a total of $N$ target atoms per unit volume, transferring of energy occur during this scattering event. The product $\sigma N dx$ represent the total fraction of the target surface area which acts as an effective scattering center to the $^{60}$Co ion. The probability of projectiles with energy $E$ undergoing a scattering event or a collision with a target nucleus while traversing a thickness $dx$ is as shown in following:

$$P(E) = N\sigma(E)dx \tag{2}$$

The total cross-section gives a measure of the probability for any type of collision to occur where energy $E$ transfers are possible. The software simulation SRIM-TRIM has simulated the trajectories and collision events of $^{60}$Co ion in LED and phototransistor based on this theory.

Figure 4 to Figure 7 show the trajectories at incidence energy level, $E_{Co} = 500$ keV and 10 MeV respectively. The red dots indicate the distribution of $^{60}$Co ion while travelling through the target atom which leads to lattice displacement. The other colours of dot clusters, however, indicate the displacement of target atom which forms a vacancy due to the recoiling of the other atoms. At $E_{Co} = 500$ keV, the lattice damage is barely on the surface of the target. As the energy is increased, the projected range started to increase and cause a deeper penetration into the device simulated.

A high energy particle loses its energy in small steps through interactions with electrons in the materials. However, once these particles have lost enough energy, the nuclear collision tends to dominate. As the particle slows down, it captures electrons to form a neutral atom. The high energy particle slows down almost entirely due to Coulomb interactions with the atomic electrons. Due to the large numbers of interaction, the slowing down procedure was nearly continuous and along a straight line path. The trapped by defects in the optical medium, giving rise to more stable secondary defects and leads to the formation of colour centers. The creation of colour centers absorbs signal photons and therefore degrading the light transmission efficiency. This will result in a decrease in the phototransistor output current for current transfer applications.

The operation of these optoelectronic devices is based on the creation or annihilation of electron-hole pairs. When the energetic particles that interact with the optoelectronic device impart energy which is equal or more than the bandgap energy to a valence band electron, pair production can occur. The bandgap energy of the GaAs semiconductor material is 1.424 eV. This pair production phenomenon can raise an electron in the valence band to the conduction band, leaving a hole behind the valence band. There is a probability that a reverse process might occur, that of electron and hole recombination, is associated with the pair releases all its excess energy after recombination. The process that occurs might be radiative recombination or non-radiative recombination. Radiative
recombination is important for the luminescent process. The non-radiative recombination, however, can reduce the radiative efficiency of the optoelectronic material.

![Figure 4](image1.png)  
**Figure 4.** Plot of depth versus Y-axis at $E_{Co} = 500$ keV in LED

![Figure 5](image2.png)  
**Figure 5.** Plot of depth versus Y-axis at $E_{Co} = 10$ MeV in LED.

![Figure 6](image3.png)  
**Figure 6.** Plot of depth versus Y-axis at $E_{Co} = 500$ keV in phototransistor.

![Figure 7](image4.png)  
**Figure 7.** Plot of depth versus Y-axis at $E_{Co} = 10$ MeV in Phototransistor.

IRLEDs emit light by means of radiative recombination of injected minority carriers with majority carriers in the depletion region. The light output is proportional to the radiative recombination current and consequently an increase of the non-radiative recombination current causes the degradation in the electrical performance of IRLED. This in turn causes degradation in the output current of the phototransistor. However, as IRLED exhibits short minority carrier lifetime as well as high current densities, thus, it exhibits higher radiation hardness.

Operating parameters can affect the level of degradation of optoelectronic devices in a given application. For the IRLED operating at a high current ($I_F = 100$ mA), the degradation formed at both the $I_C$ and $I_F$ are found to be minimized significantly. This is as when the IRLED is operated at high $I_F$, a certain amount of power that dissipated in the resistive part of the device leads to the self-heating effect.

4. **Conclusion**

When significant CTR degradation is anticipated for a specific mission application, the effect of degradation can be eventually alleviated in certain cases. This can be done by decreasing the rate of CTR or by regulating the application bias condition in order to reduce the harshness of the degradation. In other words, this anticipation is useful in the modelling of the device and also circuit
degradation in a radiation environment, without the knowledge of the exact details of the microscopic defects formed during the exposure.

From the results obtained, it is found that the degree of defect and damage produced in the optoelectronic devices highly depend on their operating current and also its mode of operation. The ionization and displacement damage induced by the incident photons have a bigger impact at these devices of low operating currents which is related to the self-annealing effect of the devices.

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