Evaluation of Static Performance of Optoelectronic Semiconductor Devices under X-rays Irradiation

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Abstract**—** Nowadays, the space technology is becoming increasingly versatile and important. Most of the important technologies such as weather forecasting, remote sensing, navigation operations, satellite television, and telecommunications systems, as well as surveillance and command-and-control operations for national security purposes critically rely on space infrastructure. Consequently, these kinds of systems are subjected to the deleterious effects of the natural space radiation environment. Furthermore, there is a growing tendency in using commercial-off-the shelf (COTS) optoelectronic devices for replacing dedicated expensive radiation hardened photonics. Expanding photonic system into such environments requires a full understanding of the effects that ionizing radiation will have on the optoelectronic properties. In this research, optoelectronic devices consisted of an infrared light emitting diode and a phototransistor with no special handling or third party-packaging were irradiated to ionizing radiation utilizing x-rays. It was found that the devices under test (DUTs) undergo performance degradation in their functional parameters during exposure to x-rays. These damaging effects are depending on their current drives and also the Total Ionizing Dose (TID) absorbed. The TID effects by x-rays are cumulative and gradually take place throughout the lifecycle of the devices exposed to radiation.

Keywords**:** optoelectronic, x-rays, Total Ionizing Dose (TID).

I. INTRODUCTION

The high-altitude nuclear test Starfish Prime was conducted by the United States of America on July 9, 1962 above Johnston Island in the Pacific Ocean. This detonation was then followed by several similar Soviet nuclear events in October [1]. The nuclear contamination as a consequential of these activities produced adequate electronic pumping on the Van Allen belts [2]. The Telstar 1 communication satellite failed not long after that as a result of the detrimental effects from the radiation in the Van Allen belts. This then rose up the necessary of intensive study on the effects of ionizing radiation on semiconductor devices.

The radiation environment that a semiconductor device encounter either at exoatmospheric or endoatmospheric [3] can be generally divided into five which are the space environment, high-energy physic experiments, nuclear environment, natural environments as well as process induced radiation. Each of these radiation environments possesses its own spectrum of particles and energy distribution. Therefore, several evaluation tests have to be done on the selected devices before they are used for the intended application.

These evaluation tests consisted of two key components: I) characterization of the radiation environment depending on the intended application and II) analyzing the radiation tolerance based on the performing parameters and manufacturing technology. The radiation effects on semiconductor devices can be categorized into four: Electromagnetic Pulse (EMP) effects, high dose rate effects, Single Event Upsets (SEU) and total dose effects [3].

EMP effects arise from the incidence of an electromagnetic wave on the semiconductor devices [4]. The resulting electric and magnetic fields from EMP may interact with electrical and electronic systems to produce damaging current and voltage surges. This effect is temporary and the system can bounce back to normal operating condition as soon as the radiation pulse terminates. Dose rate effects, however, induce a temporary failure of circuit operation which lasts as long as the radiation pulse exists. As for SEUs, it is the radiation-induced errors in semiconductor devices caused when charged particles lose energy by ionizing the medium through which they pass, leaving behind a wake of electron-hole pairs. This type of error is temporary and therefore, no permanent damage to the circuits [4].

Total dose effects, however, are permanent damage effects. Total dose effects are often associated with bulk defect creation or accumulation of trapped charge at the oxide region [5]. Consequently, the performance of

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semiconductor devices depends ultimately on the presence of defects. Total dose effects for optoelectronic devices are normally serve as the basis for parts procurement decisions. Total dose effects testing typically utilize ionizing radiation. Ionizing radiation can lead to failure in semiconductor based electronic devices due to rapid ionization events, or cause a slow continuous degradation in the performance of the devices. The work reported here primarily deals with this type of radiation damage due to TID.

This paper will present the x-ray effects on optoelectronic DUT, the radiation response of DUT and radiation tolerance of DUT to fulfill the system's operations.

II. EXPERIMENTAL DETAILS

A. Test Device Descriptions

The DUT used in this test consisted of a Plastic Infrared Light Emitting Diode (QEE 113) coupled to a Plastic Silicon Infrared Phototransistor (QSE 113). The QEE113 is a 940 nm Gallium Arsenide (GaAs) LED encapsulated in a medium wide angle and clear epoxy plastic side looker package. The QSE113, however, is a NPN silicon (Si) phototransistor encapsulated in a wide angle, infrared transparent and black plastic side looker package.

Optoelectronic devices are being discussed 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 sub-system to sub-system interfaces for space light designing's [6]. These photonics systems are ideal for applications in space system due to their high bandwidth and speed of operation, the immunity for electromagnetic interference, low power consumption and cost, yet, of high reliability [7].

B. X-ray Exposure

In this X-ray source equipment (model Toshiba KXO-12R), an exposure time selector and a milliampere-seconds (mAs) relay are connected to a computer. This controls the x-ray tube current according to the selected mAs product.

The operated potential for this x-ray machine is 40 kV and the exposure milliampere (mA) was 100 mA. The total radiation output for an exposure period is proportional to the mAs. Therefore, the absorbed dose of the DUTs could be increased by raising the mAs. Distance from the focal point of the x-ray tube to the irradiated DUT was fixed to 50cm. This was as the radiation intensity varies approximately inversely with the square of the distance. The changes in the output parameter of the DUTs were recorded and monitored at every increasing level of mAs.

C. Test Setup

The radiation testing on the electronic devices consisted of multi-parameter test with different exposure levels. Ambient temperature throughout the test was 25±3ºC. Before the irradiation process, a control test of 72 hours was performed on the DUTs. This was known as the pre-irradiation testing. Only devices which had passed the electrical specifications as defined in the test plan were submitted to radiation testing. The diagram of the test setup was as shown in Figure 1.

The information and status of the DUT were transmitted through the driver circuit based on an analog to digital converter (ADC) circuit into the PC. This driver board served as the power supply to the DUT. Moreover, it was operated as a measuring tool to real time monitor the changes in the collector current (I_C) of the reference phototransistor at various dose levels. The LED forward current (I_F) was acted as changing parameter in this experiment. Cables used to connect this system should never be led to any serious distortion of the shape of signals or the degradation of reliability in data communication.

The schematic of experimental setup for coupling the infrared emitting LED to phototransistor was as shown in Figure 2. The I_C and I_F of the phototransistor were measured *in situ* at bias I_F of 25mA, 50mA, 75mA and 100mA. The effects of TID on the current transfer ratio (CTR) of optoelectronic devices were investigated. CTR is defined as the ratio of I_C in the phototransistor to the I_F of the infrared emitter LED [X, Li. And M. Park].

$$CTR = \frac{I_C}{I_F} \quad (1)$$

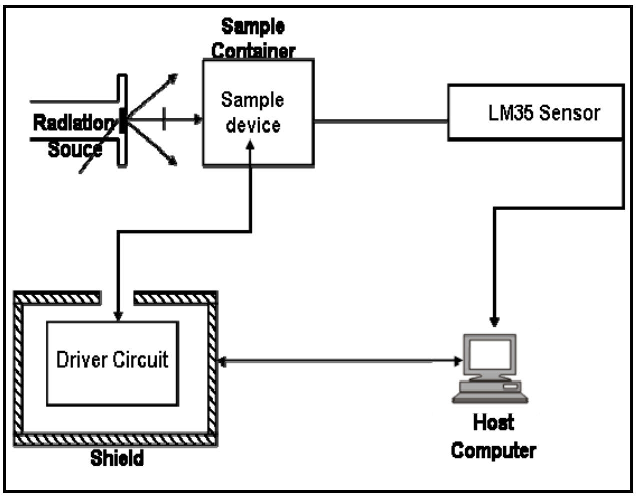

Figure 1. X-ray Irradiation Test Setup.

The Schematic of experimental setup for coupling the infrared emitting LED to phototransistor was as shown in Figure 2.

I_F (mA)	Relative Change of I_C during Irradiation(%)		
	Max. Value	Mean Value	Standard Deviation
25	1.011904	0.579328	0.284112
50	0.959416	0.515066	0.281701
75	0.854657	0.442635	0.274284
100	0.800506	0.369606	0.252369

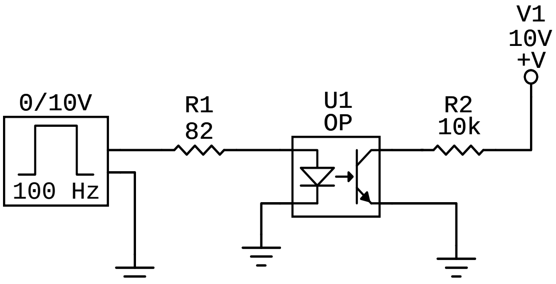

Figure 2. Schematic of Experimental Setup for Infrared Emitting LED coupled to Phototransistor.

III. RESULTS

Exposures were done on ten pairs of optoelectronic devices at multi parameter and the change in characteristics were monitored in situ at V_{CC} = 10V. Figure 3 shows the percentage change in the I_C at different bias I_F during radiation while Figure 4 shows the post-irradiation state where

$$\%\Delta I_C = \frac{I_{C1} - I_{C0}}{I_{C0}}$$

(2)

Figure 5 shows the percentage change in the I_F at different bias I_F during irradiation. The post-irradiation state, however, is as shown in Figure 6 where

$$\%\Delta I_F = \frac{I_{F1} - I_{F0}}{I_{F0}}$$

(3)

Exposure to radiation would change the value of bias I_F.

The change in the $\frac{CTR}{CTR_o}$ at different bias I_F during irradiation and at post-irradiation is as shown in Figure 7 and Figure 8 respectively.

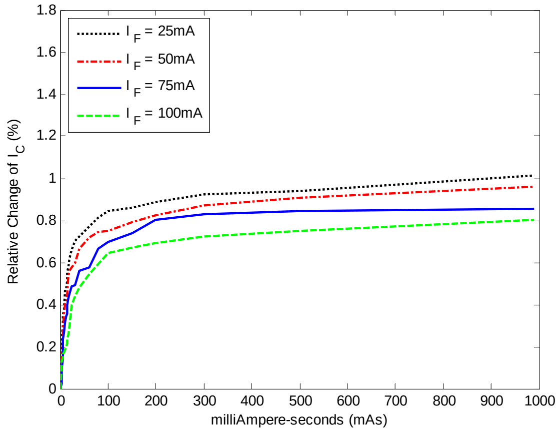

Figure 3: Relative change of Percentage Decrease in I_C of QSE113 during Irradiation for different bias I_F of QEE113.

Table 1: Statistics Data for Percentage Decrease in I_C (%) during Irradiation from Figure 3

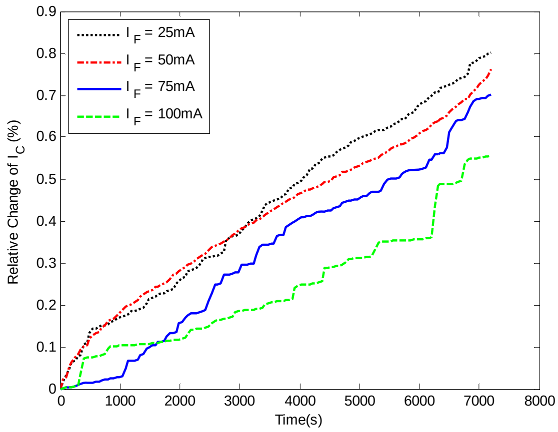

Figure 4: Relative change of Percentage Increase in I_C of QSE113 at Post-irradiation for different bias I_F of QEE113.

Table 2: Statistics Data for Percentage Increase in I_C (%) at Post-irradiation from Figure 4.

I_F (mA)	Relative Change of I_C at Post-irradiation (%)		
	Max. Value	Mean Value	Standard Deviation
25	0.800874	0.435890	0.220152
50	0.762805	0.412458	0.189795
75	0.701871	0.325384	0.210407
100	0.557608	0.240383	0.147603

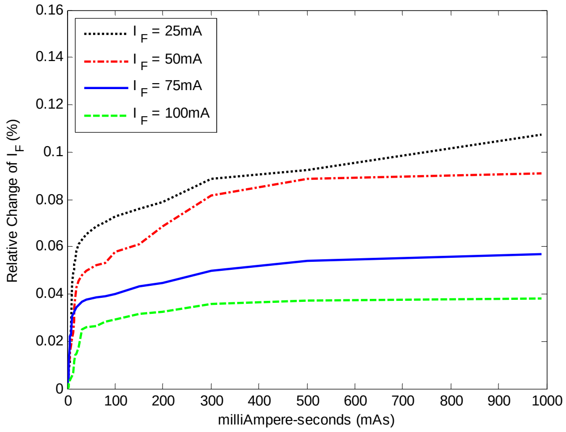

Figure 5: Relative change of Percentage Decrease in I_F of QEE113 during Irradiation for different bias I_F of QEE113.

Table 3: Statistics Data for Percentage Decrease in I_F (%) during Irradiation from Figure 5.

I_F (mA)	Relative Change of I_F during Irradiation (%)		
	Max. Value	Mean Value	Standard Deviation
25	0.107184	0.051029	0.030571
50	0.091083	0.040049	0.026299
75	0.056699	0.031297	0.015319
100	0.038199	0.016870	0.013331

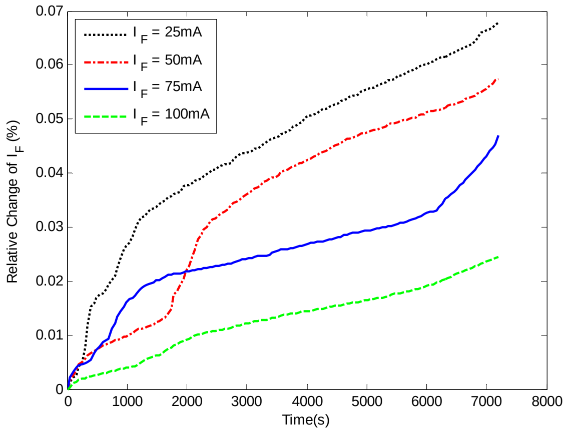

Figure 6: Relative change of Percentage Increase in I_F of QEE113 at Post-irradiation for different bias I_F of QEE113

Table 4: Statistics Data for Percentage Increase in I_F (%) at Post Irradiation from Figure 6.

I_F (mA)	Relative Change of I_F at Post-irradiation (%)		
	Max. Value	Mean Value	Standard Deviation
25	0.067893	0.044675	0.016232
50	0.057408	0.034657	0.017081
75	0.047010	0.025112	0.009546
100	0.024371	0.012814	0.006385

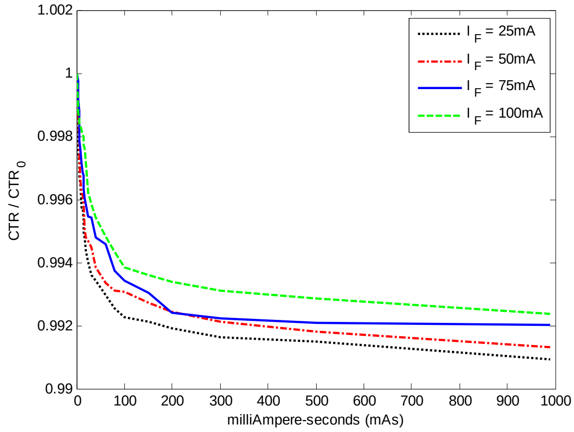

Figure 7: $\frac{CTR}{CTR_0}$ during Irradiation for different bias I_F of QEE113.

Table 5: Statistics Data for $\frac{CTR}{CTR_0}$ during Irradiation from Figure 7.

I_F (mA)	$\frac{CTR}{CTR_0}$ during Irradiation	
	Mean Value	Standard Deviation
25	0.994714	0.002545
50	0.995247	0.002565
75	0.995885	0.002597
100	0.996472	0.002393

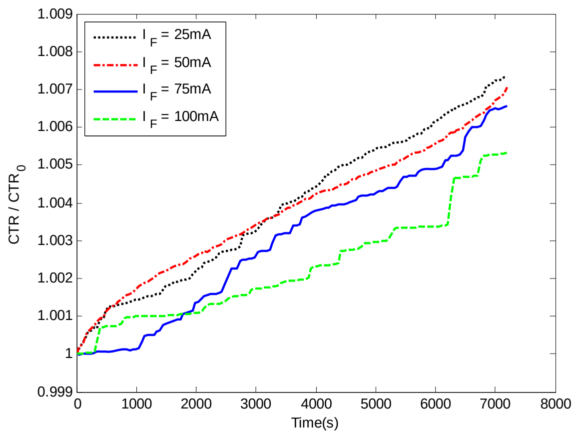

Figure 8: $\frac{CTR}{CTR_0}$ at Post-irradiation for different bias I_F of QEE113.

Table 6: Statistics Data for $\frac{CTR}{CTR_0}$ at Post-irradiation from Figure 8

I_F (mA)	$\frac{CTR}{CTR_0}$ during Irradiation	
	Mean Value	Standard Deviation
25	1.003910	0.002045
50	1.003776	0.001731
75	1.003002	0.002013
100	1.002275	0.001415

The degradation in the optoelectronic devices tested due to the exposure to x-rays is generally causing a slight decrease on the I_C, I_F and CTR. This is as shown in Figure 3, Figure 5 and Figure 7. From Figure 4, Figure 6 and Figure 8, however, it can be observed that these parameters establish a noticeable increment at a slower rate after the exclusion of exposure. This phenomenon can be explained for the fact that radiation induced excess electrons in the device substrate accumulates at the interface during the exposure and leads to the decrement in I_C, I_F and CTR. However, when the exposure is removed, these excess carriers vanish with the period through recombination and make there is a slight increment in the performing parameters.

From the plotting, it is shown that the changes in I_C and I_F with radiation are small and within specification. This is because the highest percentage drops that occurring in I_C of QSE113 at bias I_F = 25 mA is only 1.01% whereas that happening in I_F of QEE113 at bias I_F = 25 mA is only 0.11%. This is as shown in Table 1 and Table 3. The percentage of decrement in I_C and I_F almost became constant after 100 mAs. It is also clearly evidenced that I_C, I_F and CTR, indicating a higher degradation for low operating current I_F. This optoelectronic system can work almost ideally at post-irradiation.

IV. Discussions

The incident x-rays deposit their energy into materials of the devices, producing the total dose comprising of ionizing and displacement damage. Since x-rays have only energies in the range 120 eV to 120 keV, this makes x-rays deposit less energy to the materials compared to other source of radiation.

The most significant class of radiation damage in these DUTs caused by x-rays is the ionizing radiation effect. In this phenomenon, electron-hole pairs are created in the oxide. The electrons are quite mobile and move to the most positive electrode. Holes, however, with a rather complex transport mechanism, promotes the probability of trapping in the oxide volume and an associated fixed positive charge. Ionization effects are primarily determined by the interface trapped charge, oxide trapped charge, the mobility of trapped charge and also the time and voltage dependence of charge states.

LEDs 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-radiataive recombination current causes the degradation. Exposure of the LEDs to radiation causes the efficiency of radiative recombination decreases and the competing process induced will cause the device performance being degraded. These defects can serve as sites for non-radiative recombination, decreasing the efficiency of the light source.

In the LEDs, ionizing radiation causes charge to become trapped by defects in the optical medium, creating 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.

Operating parameters can affect the level of degradation of optoelectronic devices in a given application. For the infrared LED operating at almost saturated condition (I_F =100 mA), radiation induced charges in the LED output will have lesser effects on the phototransistor's output.

From the results, it is also found that TID has a more significant impact on Si material compared to that made of GaAs. The minimal drop of I_F in the GaAs LED shows that GaAs is a semiconductor with higher radiation hardness compared with silicon and, therefore, makes this material is normally preferable for the development of high speed microwave circuits.

V. Conclusion

When significant current transfer ratio (*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 modeling 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.

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