Radiation Hardness Test of BJTs under Designated Application

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***Abstract*—Performance and properties of bipolar junction transistor (BJT) devices are affected due to the harsh radiation environment. This report reviews the typical effects occurring in BJT devices due to irradiation with x-rays. The defect parameters on the device tested is obtained by *in situ* experimental technique. In order to study the self-annealing behaviour in BJTS due to ionizing and displacement modifications, damage efficiencies at different bias current levels are compared. The study reveals that higher gain degradation dispersion occurs at lower bias current level. Damage creation in the BJTs is dominated by the excitation mechanism of valence electron to the conduction band. This leads to the production of a large number of excited atoms and increases the holes in the valence band. The increase of holes in the base region due to trapping will increase the probability of recombination and reducing the number of electrons that reaches the collector region.**

***Index Terms*—BJTs, x-rays, *in situ*, self-annealing, excitation, recombination**

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 consequence of these activities produced adequate electronic pumping on the Van Allen belt [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 studies were initiated to understand radiation damage caused by surface-related effects in semiconductor devices which is the dominant failure mechanism in the electronics of Telstar 1. Based on the investigation, the satellite was then successfully repaired. In order to provide the needed radiation-induced annealing of radiation-induced surface damage, the electrical biases on crucial p-n junctions of bipolar transistors were modified. This research was then focused on the development of radiation hardened devices to counter the threat and improve the space systems.

The request for ever higher density with higher performance integrated circuit was another driving force for this research area. The manufacturing of such circuits utilize energetic particles or photons and this cause significant radiation damage. As a result, research is then carried out in controlling and removing the radiation damage as to ensure the proper functionality of the fabricated circuits.

The first study using semiconductors as expedient structures to explore the radiation effects originated in the late 1940s. This research area is then continued through the following decades. The arising demand of developing materials for nuclear reactors in the 1950s was also playing a role in stimulating the studies of heavy-ion induced damage processes in solids [3]. A variety of radiation such as alpha (α) particles, gamma (**γ**) rays, neutrons and electrons had been used to observe the production of lattice-displacement defects in bulk crystalline semiconductor materials [4, 5].

In 1970s, experimental studies were emphasized to understand the effects of radiation induced Single Event Effects (SEEs) which occur due to a single, energetic particle and can be classified into three effects [1]:

1) SEU or soft error is defined as radiation-induced errors in semiconductor devices caused when charged particles (usually from radiation belts or from cosmic rays) lose energy by ionizing the medium through which they pass, leaving behind a wake of electron-hole pairs. An SEU may occur in analog, digital, or optical components, or may have effects in surrounding interface circuitry [6]. SEUs typically appear as transient pulses in logic or support circuitry, or as bit flips in memory cells or registers. SEU may cause data corruption and alter program depending on the location of the upset [7]. A reset or rewriting of the device results in normal device behavior thereafter [8]. The SEU itself is not considered permanently damaging to the transistor's or circuits' functionality unlike the case of single event latch-up (SEL), single event gate rupture (SEGR), or single event burnout (SEB).

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2) SEL is a potentially destructive condition involving parasitic circuit elements forming silicon controlled rectifier (SCR). This may cause loss of device functionality due to a single-event induced current state. SELs are hard errors, and are potentially destructive [8]. The SEL results in a high operating current, above device specifications. The latched condition can destroy the device, drag down the bus voltage, or damage the power supply.
3) SEB is a condition that can cause device destruction due to a high current state in a power transistor. This event may occur when the passage of a single heavy ion forward biases the thin body region under the source of the device [9]. If the drain-to-source voltage of the device exceeds the local breakdown voltage of the parasitic bipolar, the device can burn out due to large currents and high local power dissipation. SEB's effects also include gate rupture, frozen bits, and noise. SEB susceptibility has been shown to decrease with increasing temperature.

Since most of the research and studies are emphasizing on shielding and material study, it was through this research that operating conditions and operating parameters of the system is being investigated. These factors might serve as inherent characteristic that play a major role in the ability of components to function properly in harsh radiation environment.

The damaging effects induced in the devices might be transient or continuous depending on the type of irradiation. Therefore, this research will use an appropriate method and concept which is the *in situ* method in monitoring the devices under test (DUTs) during irradiation with x-rays. Part of the research data which reveals the damage degradation in BJTs induced by γ rays had been presented in the previous work [10, 11]. This is different from the conventional measurement methods that had been previously used that the changes in output parameter of the DUTs are analyzed after irradiated by the source [12, 13]. *In situ* operation in data acquisition system produces results showing gradual changes in parameters during irradiation and therefore is a more accurate monitoring system as it improved the process monitoring; reduce product variance and higher throughput.

II. Research Methodology

In this study, the experiment of x-rays irradiation effects on the BJTs was performed in situ using a driver circuit board switching panel set up outside the irradiation chamber. The changes in the electrical parameters of the DUT resulting from radiation-induced charge were monitored at different irradiation level. This study was carried out in two stages which are the development of data acquisition system (hardware and software) and the radiation exposure process.

A. Hardware Development

The analogue to digital converter (ADC) implemented in this circuit converts continuous output measurement of the physical variables into a form suitable for digital handling. The input voltage range of the ADC used in this research is 0–10 V, therefore, when the input voltage falls outside the range; the ADC will return a value of the endpoint closest to the sampled signal. The 16-bit ADC is implemented due to its higher resolution characteristic. This is crucial in improving the accuracy and sensitivity to detect the small changes occur in the devices during irradiation.

At the beginning of each testing, conversion is initiated by activating the Start Conversion (SC) input of the ADC. At the completion of the conversion process, the End of Conversion (EOC) output of the ADC will change logic state. This signal is used to notify the controlling device that the conversion is over and that the data can be read. All the output data will be stored and displayed.

The core element of the ADC circuit is the Voltage to Frequency Converter (VFC). The VFC produces a digital pulse-train whose frequency is proportional to the voltage applied to the converter input. The construction of the VFC is as shown in Fig.1. The VFC contains two stage operational amplifiers (OA) and a precision pulse generator (NE555). The first stage OA is configured as a Miller Integrator together with an R-C network whereas the second stage OA is operated as a comparator.

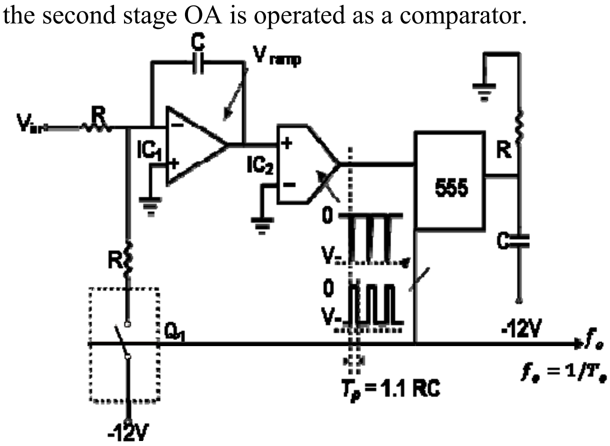

Figure 1. The Construction of Voltage to Frequency ADC.

In addition, this circuit will be integrated with digital to analogue converter (DAC) as it can function as a data dispatcher to control the DUT by receiving commands from the PC. The output generated by this DAC will be remained until it receives another value from the computer. In order to acquire and produce analog waveforms, the DAC and ADC must be activated at precise intervals. Consequently, the measuring hardware is equipped with timing circuitry to produce a pulse train of a constant frequency to control the ADC and DAC. The ADC and DAC interfaces are collectively known as semiconductor device driver circuit.

B. Software Development

The software is developed using Visual Basic programming language. It consisted of programming codes running under the DOS and Windows operating system. This software is able to perform the following operations:

The software is developed using Visual Basic programming language. It consisted of programming codes running under the DOS and Windows operating system. This software is able to perform the following operations:

1) Processing the input digital signals, including arithmetical operations, comparison, ordering, and code conversion,
2) Display in numerical form,
3) Transmission,
4) Storage for further data handling, and changing the characteristics (current and voltage) of the DUT.

An asynchronous protocol is implemented in the serial communications between the hardware and software. This protocol is very crucial in synchronizing the data transmission rate between the hardware and the computer. This synchronization will be initialized by the transmitted Start bit from the computer.

There are two important timers in this software which carry out the main task in interfacing the hardware developed. One of the timers is used to generate periodic signals which trigger the hardware circuit to output the measured data bits. Another timer is used to produce periodic signals that serve as an output latch register which returns any input value from the input buffer of the communication port.

The input analog signal has an infinite number of possible levels within its range. Therefore, the analog signals will then be converted into a fix number of possible digital states by using the encoding method. For example, to measure the changes of voltage parameter in the DUT, the following equation will be applied

$$V = \frac{\text{Encoded Decimal Value}}{65535} \times 10.0 \quad (1)$$

C. 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.

D. Test Setup

The radiation testing on the electronic devices consisted of multi-parameter test with different exposure levels at room temperature.

The input voltage of the particular device can be varied from a distance of approximately 15m in a control room during irradiation and the effect can be observed directly using in-situ method. The schematic drawing of the test setup for in-situ testing is as shown in Fig. 2. The information and status of the DUT will be transmitted through the driver circuit based on an ADC circuit into the PC. 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.

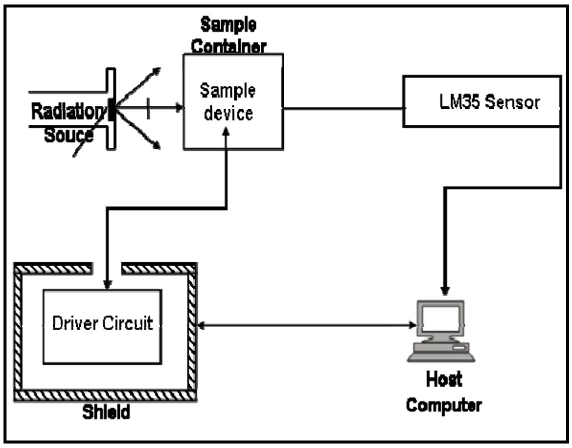

Figure 2. Experimental Arrangement for observing the changes in the DUT during Irradiation

III. RESULTS AND DISCUSSIONS

The collecting current, I_C of BJT at pre-irradiation with the readings during the radiation exposure is compared. At normal room condition (pre-irradiation), I_C retains at an almost static value. The readings of I_C decrease with the total dose absorbed during x-ray exposure. The relative change of percentage decrease in I_C during irradiation can be calculated through the Equation (2).

$$\%\Delta I_C = \left| \frac{I_{C1} - I_{C0}}{I_{C0}} \right| \times 100 \quad (2)$$

During the x-rays exposure, the BJTs are found to exhibit a characteristic of rapid increasing in relative change of I_C at almost linear manner for radiation less than 100 mAs as shown in Fig. 3.

For radiation level beyond 100 mAs, the relative change of I_C is being reduced up to radiation level of 1000 mAs which implied that ΔI_C is more saturated at higher dose level. In addition, the results also indicated that the lower bias current levels result in larger gain degradation dispersion. With higher operating bias current of I_C, the static performance is less sensitive to the ionizing radiation effects.

The effect on base current, I_B of 2N3904 at different states for different bias current of I_C are compared. During the irradiation process, it is observed that the I_B is increasing with the dose absorbed. Considering the relative change of I_B, it shows a characteristic of rapid increasing for radiation less than 100 mAs as shown in Fig. 4. The inclination gradient at the plane, however, is reduced for radiation level beyond 100 mAs and up to 1000 mAs.

Gummel plot of BJT is essential in presenting the electric currents, I_C and I_B versus V_{BE} in a combined plot with semi-logarithmic scale to show the common-emitter transfer characteristics of BJT in the forward active regime while the V_{BC} is kept at constant. Fig. 5 is plotted using the post-irradiated values after exposure to the radiation at ON mode.

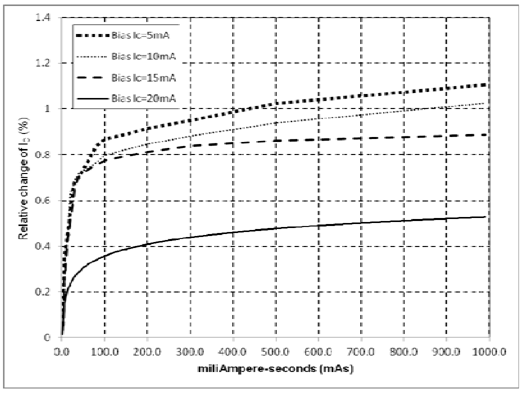

Figure 3. Relative change of percentage decrease in I_C of the BJT 2N3904 during irradiation for different bias of I_C.

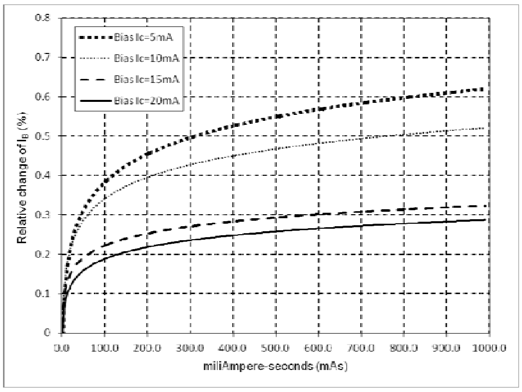

Figure 4. Relative change of percentage increase in I_B of the BJT 2N3904 during irradiation for different bias of I_C.

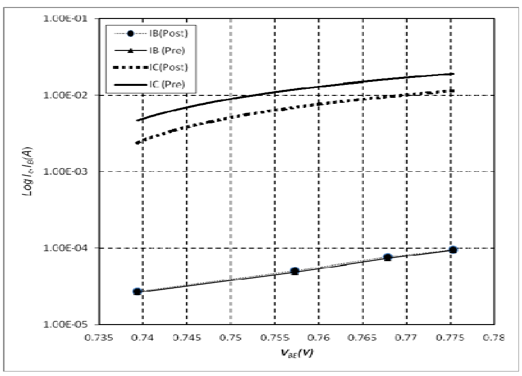

Figure 5. Gummel Curve of the BJT 2N3904 at before irradiation and after exposed to 1000 mAs x-rays at ON mode.

From the result as shown in Fig. 6, the transconductance, g_m, of the BJT is found to be having very closed readings after being exposure to a total dose of 1000 mAs of x-rays. Hence it can be concluded that the g_m of BJT do not sustain much degradation after the irradiation.

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 common emitter current gain, 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.

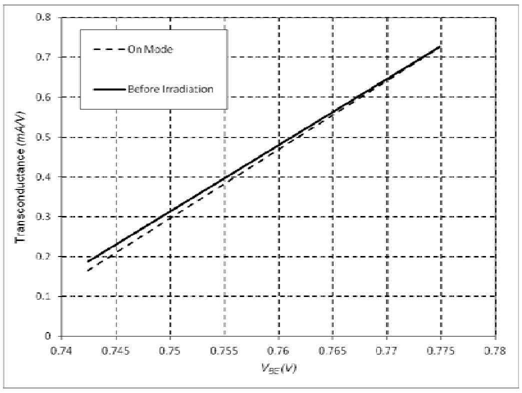

Figure 6. Transconductance (g_m) of the BJT 2N3904 at before irradiation and after exposed to 1000 mAs x-rays at ON mode.

The most significant class of damage induced by x-rays in the BJT is the ionizing radiation effect. X-rays do not cause direct displacement damage, since momentum conservation sets the threshold energy of 250 keV for photons. 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 x-rays 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 Fig. 7 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.

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 can be seen from the increase of non-ideal I_B and decrease of I_C which in turn leads to the reduction of h_{fe}.

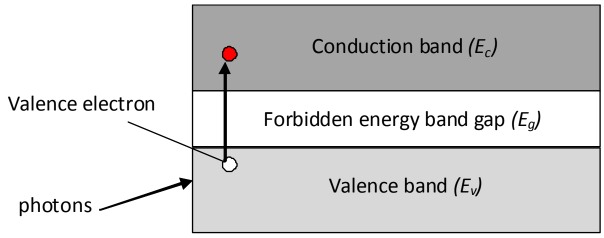

Figure 7. Excitation of electrons from valence to the conduction band.

IV. Conclusion

The high energy of the radiation allows more valence electrons to be excited to the conduction band. This leads to the production of a large number of excited atoms and increases the holes in the valence band. This phenomenon is known as the creation of electron-hole pairs in the BJT device. The increase of holes in the base region due to trapping will increase the probability of recombination and reducing the number of electrons that reaches the collector region.

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