The Effects of γ-rays on Power Devices

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Abstract: The electrical characteristics of power devices such as BJT (Bipolar Junction Transistor), and MOSFET (Metal Oxide Field Effect Transistor), etc, are altered due to impinging photon radiation and temperature in the nuclear or the space environment. In this paper, BJT and MOSFET are the two devices subjected to γ radiation. In the case of BJT, the current gain (β) and the collector to Emiter breakdown voltage (V_{CEO}) are the two main parameters considered. When it was subjected to γ rays, the β decreases as the dose level increases, whereas, V_{CEO} gradually increases as the dose level increases. In the case of MOSFET, the threshold voltage is decreasing as the dose level increases. Here it has been observed the decent rate is an increasing function of the threshold voltage. The on-resistance does not change with respect to the dose. Both the devices recover back the original specification after the annealing is finished. No permanent damage has been occurred.

Keywords: transistor, MOSFET, gain, irradiation, threshold voltage, on-resistance

1. INTRODUCTION

The radiation hardening parts are to be used for satellite and nuclear power plant since there exist various kinds of radiation particles in space and radiation environment. For the past 40 years, the countries with advance of satellite technology are doing research in the field of radiation effects of passive and active components for electronic circuit mainly for space and defence. The researchers in these countries have been sharing many reports that lead to exchanges of satellite technology. However, the level of the technology in Korea is far behind and it is the time for all researches to focus our attention.

In order to subject the components and the circuits in the radiation environment, we need the radiation simulation facility. The types of radiation are generally divided into particle radiation and photon radiation. The particle radiation consists of the charged particles which have protons, electrons, a particles, ions, and neutral particles that are the neutrons.

The particle radiation may also induce ionization so that excess carriers are generated within a semiconductor materials and devices. The photon radiation consists of γ-rays and/or x-rays. The units primarily used in radiation effects work which deal with ionization effects induced by γ-ray are rad. The rad is the amount of radiation which deposits 100 ergs of energy per gram of material. When dealing with particle radiation, the units are flux (number/cm^2-sec) and fluence (number/cm^2).

A simple elegant method for estimating the threshold voltage shift [1] due to low dose rate ironizing irradiation was recently proposed for power MOSFETs. Briefly, the method consists of estimating at the low dose and summing the threshold shift due to the oxide charge trapping at the surface of the p-n junction immediately after irradiation and annealing 100 °C.

2. RADIATION EFFECTS ON POWER DEVICES

The current gain (β) and breakdown voltage of the transistor and the threshold voltage(Vth) and the on-resistance (R_{DSON}) of MOSFET (V_{DSS} =100V) is tested and compared with the specifications under the pre-irradiation. The irradiation dose rate is 4.97 rad/sec, and maximum total dose is 30 Krad. The test procedure and method confirms Mil-Std-883 Method 1019. The γ source using ^{60}Co is used for the test of commercial power products. The sample sizes of testing transistors and MOSFET's are 5 or 6 pieces each.

2.1 Transistor

Many experimental results in the technical report[2] were suggested for estimating the relationship between the current gain and the dose. The value of β for pre-irradiation is, in general, more than 150, the one of β has tendency of decreasing to 30 in NPN transistor, and to 20 in PNP transistor for more than the dose of 1 Mrad.

When the transistor is irradiated under nutron, Messenger - Spratt [2] characterizes as

$$\frac{1}{\beta_{post}} = \frac{1}{\beta_{pre}} + 10^{-7}\frac{\phi_n}{f_T} \qquad (1)$$

where β_{post} the gain of post-irradiation, β_{pre} the gain of pre-irradiation, ϕ_n the dose, f_T is unity gain frequency. As the quantity of dose increases for the specified f_T, the current gain β decreases since the collector current of transistor is much affected in the radiation. It is important to set up the model for the radiation of characteristics of the electronic components under the same conditions as the space environment. There are some difficulties in obtaining precise data since the advanced countries developing radiation hardening technologies are classified in nature, and do not want to share with other countries. In this paper, the model of characteristics of BJT is obtained from P-SPICE [3] circuit simulator of Microsim company.

The Fig. 1 shows the relationship of current gain vs. the collector current (I_C) for the total neutron dose 2.5×10^{12}, 3.6×10^{12}, 1×10^{13}, 1×10^{14} particles/cm^2. The current gain of 2N2222 has more than 200 at the pre-irradiation, but abruptly decreases as the dose of neutron irradiation increases [4]. The reason for reduction in the current gain is due to the reduced lifetime of minority carrier of BJT and the increased leakage current by the damage of the surface state. The damage can be produced by the collision of neutron particles.

The current gains in the transistor are decreasing exponentially as the neutron dose increases up to 1×10^{14} particles/cm^2 under the collector current (I_C) of 10 mA as shown in Fig. 2.

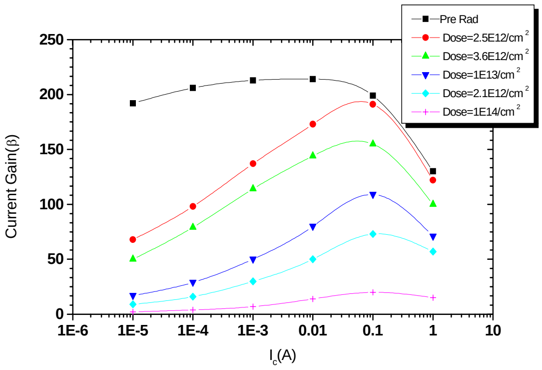

Fig.1 Relationships between the current gains vs. collector currents under the neutron radiation dose

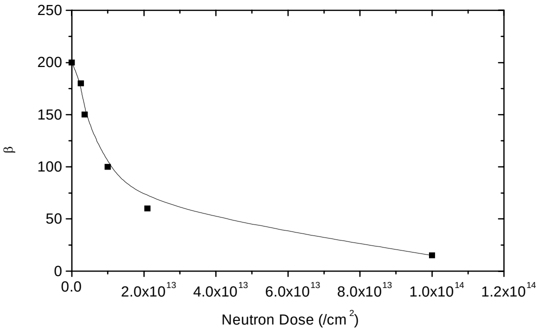

Fig.2 Current gain for each neutron dose of Ic=10 mA

2.2 Power MOSFET

MOS devices are among the most sensitive of all semiconductors to radiation, in particular, ionizing radiation, showing much change to even relatively low doses. In fact, the effects of radiation on MOS devices must be at about the same level of total dose. Duration and dose rate are related to total dose given by R. E. Sharp [5]. The gate field oxide structures give the main influence on the changes in electrical characteristics [5, 6] due to irradiation. A simple translation of the I-V characteristic towards more negative values of gate voltage is brought by oxide trapped charge. This is much serious for n-channel devices when the I-V curve is shifted past zero volts as the current increases sharply. This effect is often considered as a change in gate threshold voltage. The main effect is a distortion of the I-V curve of the device which in turn lower the transconductance.

3. EXPERIMENT RESULTS

3.1 Transistor

The I_C-V_{CE} characteristics for a pre-irradiated transistor is given in Fig. 3. The gain of β is 173.2 and the maximum value of I_C is 3.464mA. We observe in saturation that both I_C and V_{CE} are nearly independent of I_B. A change in I_B from 4 to 20 uA indicates about a 40 mV change in V_{CE} (saturation) and, even on an expanded scale, an imperceptible change in I_C.

The gain parameter β is related I_C and I_B in saturation as

$$\beta = \frac{I_C}{I_B} \mid \text{in saturation} \qquad (2)$$

Fig. 4 shows I_C-V_{CE} characteristics for a irradiated transistor. The gain of β and the value of I_C is decreased to 131.25 and 2.625 mA, respectively. The intervals among the 5 lines are narrowed compared with those of Fig. 3.

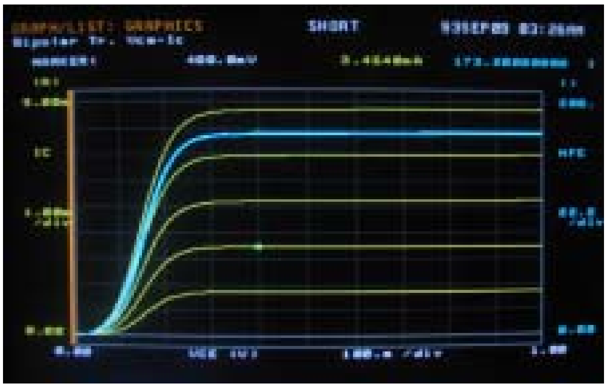

Fig.3 I_C-V_{CE} characteristics of a pre-irradiated transistor (β = 173.2, I_C = 3.464 mA)

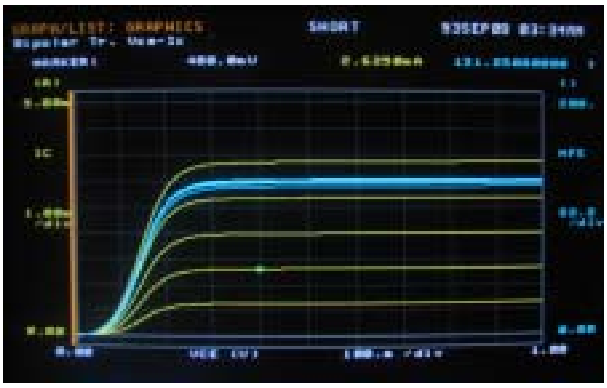

Fig. 4 I_C-V_{CE} characteristics of a irradiated transistor (total dose 5 Krad, dose rate 4.97 rad/sec, β = 131.25, I_C = 2.625 mA)

The Gummel plots [1] of Fig. 5 and Fig. 6 for representing I_B (base current) and I_C (collector current) are measured by setting V_{CE} as constant and V_{BE} as variable.

The current gain (β) of pre-irradiation in Fig. 5 shows approximately 176, and that of post-irradiation of 20 Krad with dose rate 4.97 rad/sec given in Fig. 6 is decreased to 71. The results satisfy the equations under reference [2].

Fig. 5 shows the constant interval of I_C and I_B. As the voltage increases, the upper line of I_C goes downward, but the lower line of I_B goes up, and the value is decreased as shown in Fig. 6. The fact says that the minority carrier of the transistor under post-irradiation flows more than that under pre-irradiation.

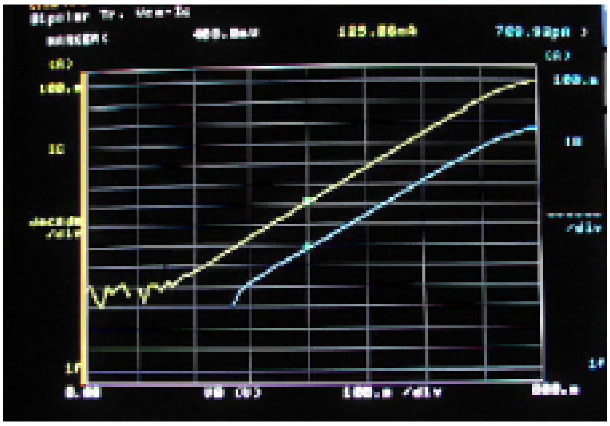

Fig.5 Current gain (β =176.16, Ic = 125.06 nA, I_B = 709.92 pA) characteristics of Gummel Poon Model (pre-irradiation)

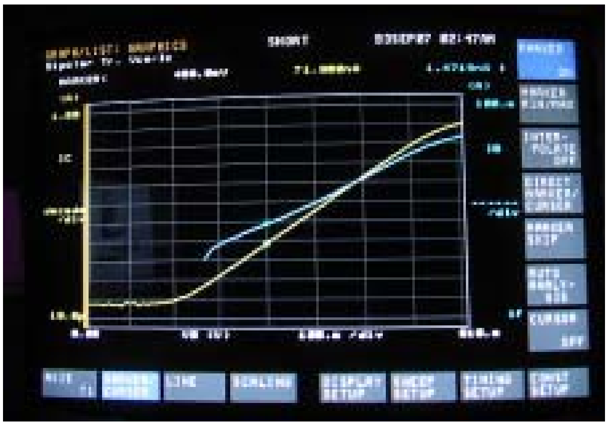

Fig.6 Current gain (β) characteristics of Gummel Poon Model (total dose 20 Krad, dose rate 4.97 rad/sec)

Fig. 7 shows the current gain of β. The current characteristics of irradiated transistor show based on quantity of dose and after annealing at 100 °C and 168 hours. The quantities of doses are 0, 5, 10, 15, 20, and 30 Krad, respectively, and the dose rate is 4.97 rad/sec. As the quantity of dose increases, the value of β decreases, up to 30 Krad, but the current of β is recovered to some degree at the level of 20 Krad after annealing at 100 °C and 168 hours.

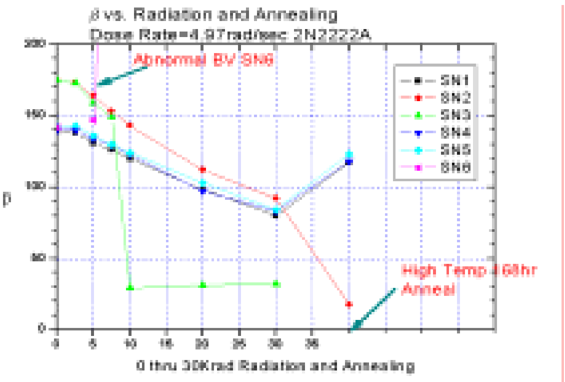

Fig.7 Current gain (β) characteristics of a irradiated transistor (dose rate 4.97 rad/sec)

The breakdown voltage plot in Fig. 8 is continuously increasing due to the charge trapping at the surface of p-n junction as the quantity of dose increases up to 30 Krad, but the ones are recovered to the value of 10 Krad after annealing.

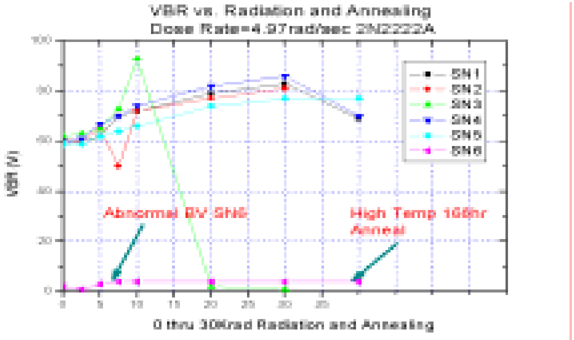

Fig.8 Breakdown voltage (V_{BR}) characteristics of a irradiated transistor (dose rate 4.97 rad/sec)

3.2 Power MOSFET

The commercial IR (International Rectifier) MOSFET products are chosen for test. The sample size of testing is 5 pieces for each test.

Fig. 9 and 10 show threshold voltage and on-resistance characteristics of irradiated MOSFETs based on quantity of dose and after annealing at 100 °C and 168 hours. The quantities of doses are 0, 5, 10, 15, 20, and 30 Krad, respectively, and the dose rate is 4.97 rad/sec. The annealing at 100 °C and 168 hours is carried out right after irradiation.

As shown in Fig. 9, the threshold voltage of MOSFET is decreasing as the quantity of the total dose increases up to 30 Krad with dose rate of 4.97 rad/sec, but the voltage was not recovered after annealing 100 °C and 168 hours. The voltage was recovered to the level of 20 Krad irradiation with 4.97 rad/sec of 2.6 V in Fig. 9, which is satisfied with the minimum requirement of 2.0 V.

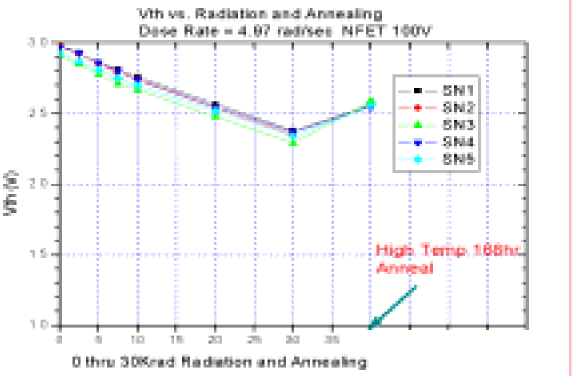

Fig.9 Threshold voltage characteristics of a MOSFET (100 V).

The on-resistance characteristics are shown in Fig. 10, and the results are met with the specification of maximum 0.077 ohm. The on-resistance of the device does not greatly change after the annealing is finished.

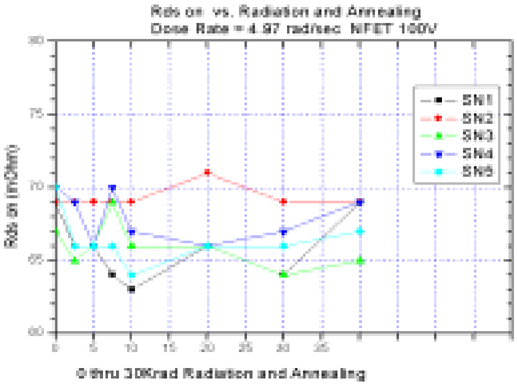

Fig.10 On-resistance (R_{DSON}) characteristics of a N-FET (100 V) based on quantity of dose and after annealing at 100 °C and 168 hours (dose rate 4.97 rad/sec)

4. CONCLUSION

The results of the current gain obtained in the experiment for the commercial transistor are proved and satisfied the eq. (1). The failure rate in measuring breakdown voltage and current gain to γ-radiation of 30 Krad dose is about 30 %, i.e. 2 of 6 pieces, which is higher than that of the quality control in the commercial manufacturing line. This method can be used to screen the commercial components for satellite and nuclear power plant applications which will reduce the cost and procurement time of Mil-spec. components.

When we apply radiation, the slope descent rate of the threshold voltage reduces linearly as the total dose increases, but the voltages at the doses of 0 to 30 Krad are satisfied with the requirement. The on-resistance does not change with respect to the dose. The two experiments show that IR commercial products are robust in the radiation.

ACKNOWLEDGMENTS

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