Impact of Gamma Irradiation Effects on IGBT and Design Parameter Considerations

Young Hwan Lho

ABSTRACT—The primary dose effects on an insulated gate bipolar transistor (IGBT) irradiated with a ^{60}Co gamma-ray source are found in both of the components of the threshold shifting due to oxide charge trapping in the MOS and the reduction of current gain in the bipolar transistor. In this letter, the IGBT macro-model incorporating irradiation is implemented, and the electrical characteristics are analyzed by SPICE simulation and experiments. In addition, the collector current characteristics as a function of gate emitter voltage, V_{GE}, are compared with the model considering the radiation damage of different doses under positive biases.

Keywords—Radiation effect, IGBT, MOS, bipolar transistor.

I. Introduction

Radiation is generally divided into two types: particle radiation and photon radiation. Particle radiation consists of charged particles such as protons, electrons, α particles, ions, and neutral particles called neutrons. Photon radiation consists of γ-rays and/or x-rays.

A simple method for estimating the threshold voltage shift due to ionizing irradiation at low dose rates was recently proposed for power MOSFETs [1]. The method consists of estimating the threshold voltage shift due to oxide charge trapping at the MOS immediately after irradiation.

The insulated gate bipolar transistor (IGBT) combines the advantages of a power MOSFET [1], [2] and a bipolar power transistor. The input has an MOS gate structure, and the output is a wide-base PNP transistor. The base drive current for the PNP transistor is fed through the MOSFET at the gate. In conduction mode, the epitaxial region is conductivity modulated by excess holes and electrons thereby eliminating a major component of the on-resistance.

The basic equivalent circuit of IGBT is shown in Fig. 1.

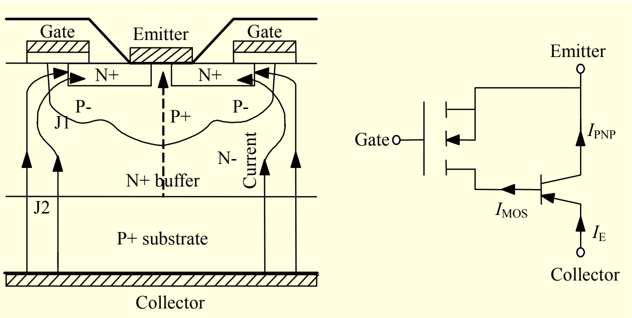

Fig. 1. Basic equivalent circuit of IGBT.

II. Radiation Effects on IGBT

MOS devices are among the most sensitive of all semiconductors to radiation, particularly ionizing radiation, showing much change even after a relatively low dose. This effect is often considered as a change in gate threshold voltage.

The relationship between threshold voltage V_T and charge Q_{tot} in SiO$_2$ is given by

$$\Delta V_T = -\frac{\Delta Q_{tot}}{C_{ox}}, \tag{1}$$

where C_{ox} is fixed for each kind of gate oxide capacitance, and the change of charge, ΔQ_{tot}, depends on the dose. The change of threshold voltage, ΔV_T, is proportional to ΔQ_{tot}.

1. SPICE Model

To analyze the radiation effects based on the circuit model as

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Young Hwan Lho (phone: +82 42 629 6731, email: yhlho@wsu.ac.kr) is with the Department of Railroad Electricity and Information Communication, Woosong University, Daejeon, Rep. of Korea.

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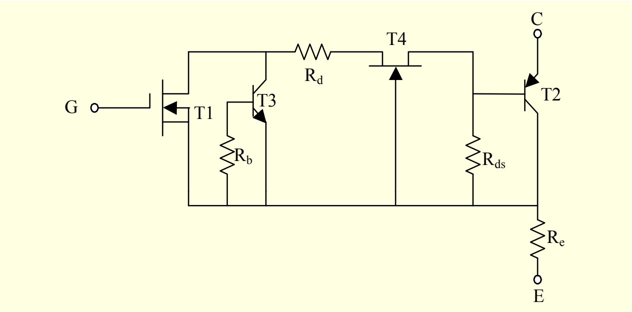

Fig. 2. SPICE model of IGBT.

Table 1. SPICE parameter values of T1 and T2.

MOS parameters	Level = 1, V_T = 6.5 V, K_P = 0.5 A/V^2
BJT parameters	IS = 10^{-16} A, BF (β) = 10, NE = 2

shown in Fig. 2, we adopted the SPICE model supplied by the IGBT maker, International Rectifier (IR). The IGBT SPICE micro-model with a parameter variation considering dependence of the radiation damage allows the designer to estimate the performance to find the optimal condition of systems including IGBTs under irradiation environments [3], [4].

The model was simplified by removing all elements relating to transistor dynamic behavior. We modified the SPICE model of 1,200-V 45-A IGBT IRG4PH50S from IR to reproduce the changes of electrical parameters [3] that occur during the radiation tests. T1 is the input MOSFET. It is a level 1 SPICE model [5].

Our study is concerned mainly with the changes in parameters β (forward current gain), K_P (MOS transconductance), and V_T (threshold voltage) shown in Table 1. Here, V_T is the gate voltage connected to the collector at I_C=100 mA. Other factors are not significantly impacted by irradiation [1].

2. Comparison Simulations with Experiments

At low total dose rates in our simulations, the V_T shift is the major contributor to the current increase, but for a dose of more than 100 krad [4], the current decreases because of the current gain degradation that occurs in the vertical PNP at the output of the IGBTs, in which the PNP transistor is located at the substrate. However, the current gain β is not greatly reduced at low doses because the depth of the emitter base junction is formed at the substrate region. The decrease of current gain in the bipolar transistor affects the increase of V_{GE}. The experimental results of exposing IGBT samples to a gamma radiation source show shifting of the threshold voltages in the MOSFET, and degradation of the carrier mobility and current gains. The collector current characteristics as a function of the gate emitter voltage curves are analyzed with the model considering the effect of radiation on the devices at different doses.

Table 2. Parameter values of M_β and M_T for positive biases (I_C= 100 mA, K_P=0.5 A/V^2, β_{pre}=10, V_T=6.5 V).

V_{GE} (V)	M_β	M_T (V/krad)
0	0.08	0.037
2.5	0.08	0.048
5	0.08	0.059
10	0.10	0.063

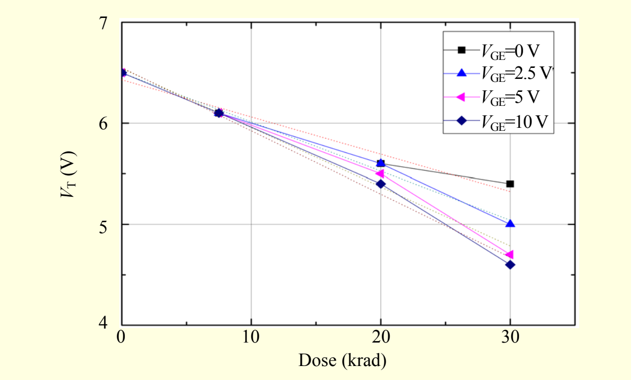

Fig. 3. V_T vs. doses for positive bias at I_C=100 mA.

Table 2 shows the current gain reduction coefficients (M_β) and the threshold reduction coefficients (M_T) for positive gate biases.

Figure 3 shows the simulation results as dotted lines and the experimental as solid lines in terms of V_T versus doses. Charge trapping occurs at the gate of the MOSFET (T1) as shown in Fig. 2, and the change of V_T decreases less rapidly as the gate bias voltages (0 V, 2.5 V, 5 V, and 10 V) are increased because the depletion region under the MOS is expanded. The applied doses are 0 krad, 7.5 krad, 20 krad, and 30 krad for a positive bias of I_C=100 mA. The sub-threshold current increases for the surface leakage under higher dose levels. Therefore, V_{GE} in T1 should be lower to achieve the same collector current I_C for T2.

The electrical characteristic is mainly affected by two phenomena. One is an interface trap buildup in T1, and the other is a drop of current gain BF in T2. Figure 4 shows the threshold reduction coefficients in terms of the bias voltages of 0 V, 2.5 V, 5 V, and 10 V, respectively.

When the transistor operates in the saturation region, I_C is calculated as

$$I_C = \beta \cdot K_P (V_{GE} - V_T)^2, \tag{2}$$

where β and V_T are used to calculate I_C, and V_{GE} is obtained

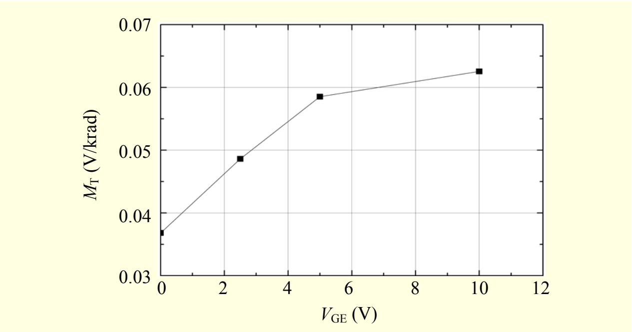

Fig. 4. Threshold reduction coefficients (M_T) vs. positive gate biases.

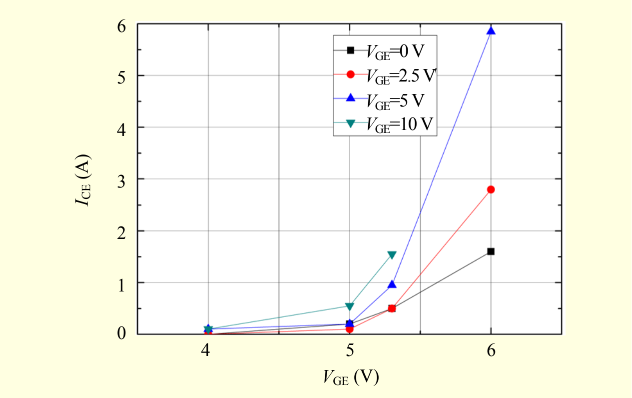

Fig. 5. I_{CE} vs. V_{GE} for positive gate biases under 30 krad.

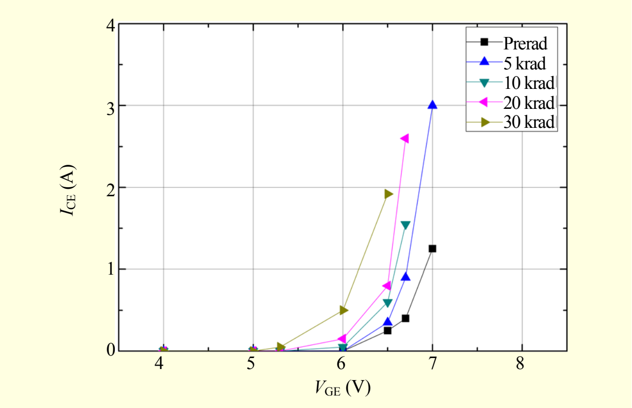

Fig. 6. I_{CE} vs. V_{GE} at the applied doses for positive bias (V_{GE} = 0 V).

from (2) as

$$V_{GE} = V_T + \sqrt{\frac{I_C}{\beta \cdot K_P}}. \tag{3}$$

In (3), V_T is computed as

$$V_T = V_{T0} - M_T \cdot \phi, \tag{4}$$

where V_{T0} is the pre-irradiated threshold voltage, M_T is the threshold reduction coefficient, and ϕ is the total dose irradiation.

In the experiments, the 1,200-V IGBTs (IRG4PG50S) showed slopes of M_T at doses of 0 to 30 krad ranging from 0.037 to 0.063 as seen in Fig. 4. The slope gets steeper as V_{GE} increases.

As seen in Fig. 5, the collector-emitter currents, I_{CE}, of the positive biased IGBT show a more drastic reduction than negatively biased ones with increasing doses [4]. The positive bias voltages induce an expansion of the depletion region under the MOS, which results in increasing the possibility of capturing negative charges at the MOS. This reduces V_T and the current gain; thus, the slope of the I_{CE} curve decreases.

Figure 6 shows the experimental results of I_{CE} versus V_{GE} voltage for positive bias (V_{GE}=0 V) at the applied doses of pre-irradiation, 5 krad, 10 krad, 20 krad, and 30 krad. As the dose increases, the slope becomes steeper than at lower doses under the same bias voltage. The I_{CE} curve is met with the square law of (2) above the threshold voltage, and the current in the sub-threshold increases because there is a surface leakage current in the MOS gate region. Trapped positive charges in the MOS cause reduction of carriers in the *p* base region, in which an NPN transistor is formed under the MOSFET channel region. An increase of the collector-base depletion region results in the enlargement of both the collector base junction thermal current and the surface leakage current. The base current is kept in transistor T2, and this current corresponds to the measured collector output current multiplied by the current gain of β.

III. Conclusion

The characteristics of an IGBT were simulated by SPICE and compared with experimental results from exposure to various gamma radiation doses under gate biases. The experiment results compare well with the simulation ones. The results allow engineers to design optimized circuits for the power system. The dominant factors in radiation effects are threshold voltage reduction and current gain.

References

[1] Y.H. Lho and K.Y. Kim, "Radiation Effects on the Power MOSFET for Space Applications," *ETRI J.*, vol. 27, no. 4, Aug. 2005, pp. 449-452.

[2] Y.K. Cho, T.M. Roh, and J. Kim, "A New Strained-Si Channel High Voltage MOSFET for High Performance Power Applications," *ETRI J.*, vol. 28, no. 2, Apr. 2006, pp. 253-256.

[3] M. Marceau et al., "Study of Dose Effects on IGBT-Type Devices Subjected to Gamma Irradiation," *IEEE Trans. Nucl. Sci.*, vol. 46, no. 6, Dec. 1999, pp. 1680-1685.

[4] Y.H. Lho et al., "Radiation Effects on IGBT under Gamma Irradiation," *Int. Conf. Control, Autom. Syst.*, Oct. 17-20, 2007, pp. 893-896.

[5] SPICE Reference Guide, Cadence Design Systems, 2000.