게이트바이어스에서 감마방사선의 IGBT 전기적특성

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Electrical Characteristics of IGBT for Gate Bias under γ Irradiation

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Abstract - The experimental results of exposing IGBT (Insulated Gate Bipolar Transistor) samples to gamma radiation source show shifting of threshold voltages in the MOSFET and degradation of carrier mobility and current gains. At low total dose rate, the shift of threshold voltage is the major contribution of current increases, but for more than some total dose, the current is increased because of the current gain degradation occurred in the vertical PNP at the output of the IGBTs. In the paper, the collector current characteristics as a function of gate emitter voltage (VGE) curves are tested and analyzed with the model considering the radiation damage on the devices for gate bias and different dose. In addition, the model parameters between simulations and experiments are found and studied.

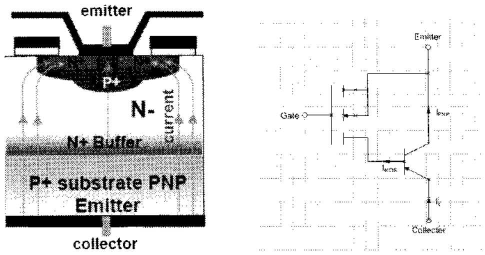
Keywords - IGBT, γ Irradiation, bipolar transistor, MOS

1. INTRODUCTION

Electronic radiation hardening parts are used for satellite and nuclear power plants since various kinds of radiation particles exist in space and radiation environments. For the past 50 years, countries with advanced satellite technology have been conducting research in the field of radiation effects for passive and active components of electronic circuits, mainly of space and defence usages. Generally, there are two radiation types: particle radiation and photon radiation. In particle radiation, the charged particles can be protons, electrons, α particles, ions, or neutrons. The photon radiation consists of γ rays and/or x-rays. A simple method for estimating the threshold voltage shift[1] due to the ionizing irradiation of low dose rate was recently proposed for power MOSFETs. Briefly, the methods consists of estimating the threshold voltage shift by the oxide charge trapping at the gate oxide immediately after irradiation.

The IGBT combines the advantages of a power MOSFET[2] and a bipolar power transistor. The input has a 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 fabrication process is similar to that of an n-channel power MOSFET except the epitaxial layer grown on a p+ substrate.

The IGBT has merits on other power devices (a) High current density and low on-state voltage drop. (b) Low driving power and a simple drive circuit due to the input MOS gate structure. (c) Because of superior conduction capability, it has excellent forward and reverse blocking capabilities and wide SOA. The drawback of IGBT is mainly on the switching speed and latch up problems. (a) Switching speed is inferior to that of the power MOSFETs. (b) There is the possibility of latch-up due to the internal PNPN thyristor structure. The holding current is reduced when exposed to a radiation sources.



<Fig. 1.1> Basic equivalent circuit of IGBT

2. RADIATION EFFECTS ON IGBT

2.1 Threshold Voltage Shift

MOS devices are among the most sensitive of all semiconductor to radiation, in particular ionizing radiation, showing much change even after a relatively low dose. In fact, the effects of radiation on MOS devices must be at about the same level of total dose. The gate oxide structures give the main influence on the changes in the electrical characteristics [1] affected by irradiation. A change of the I-V characteristic towards more negative values of gate voltage is brought by charge trapping at the gate oxide. 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 relation between threshold voltage V_T and charge Q_{tot} in SiO_2 is given by

$$\triangle Q_{tot} = -C_{ox} \triangle V_{th} \qquad (2.1)$$

where C_{ox} is fixed for each different kind of MOSFET, and $\triangle Q_{tot}$ depends on the dose.

2.2 Reduction of Current Gain

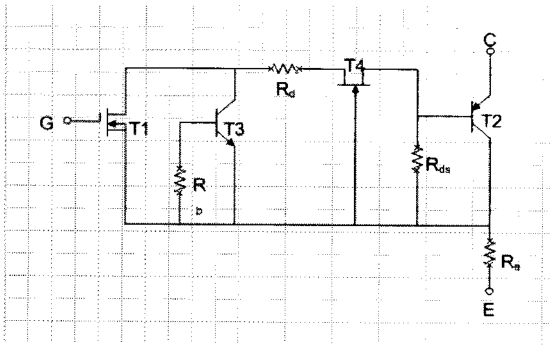
Many experimental results in the technical report [3,4,5] were suggested for estimating the relationship between the current gain (β) and the dose. The value of β for pre-irradiation is, in general, more than 150, the one of β has tendency of decreasing to 30 in NPN transistor, and to 20 in PNP transistor for more than the dose of 1 Mrad. When the transistor is irradiated under neutron, Messenger-Spratt [5] characterizes as

$$\frac{1}{\beta_{post}} = \frac{1}{\beta_{pre}} + M_{\beta}\Phi n \qquad (2.2)$$

As the quantity of dose increases, the current gain β decreases since the base current has increased due to the reduction of carrier life time in the base region and the increase of leakage current at the surface of base region.

3. DESCRIPTION OF MODEL

3.1 SPICE Model



<Fig. 3.1> SPICE Model of IGBT

The change of electrical characteristics for irradiated IGBT is mainly coming from the change of characteristics of MOSFET at the input gate and the PNP transistors at the output. To analyze the radiation effects based on the circuit model as shown in Fig. 3.1, we adapt the SPICE [5] model supplied from the IGBT makers. The IGBT SPICE micro-model with a parameter variation depend on the radiation damage allow the designer to estimate the performance to find the optimal condition of systems including IGBTs under irradiation environments.

The model was simplified by removing all elements relating to transistor dynamic behavior. We modify the SPICE model of 1200V 45A IGBT IRG4PH50UD from IR to reproduce the change of electrical parameters occurred during the radiation tests.

Table 3.1 SPICE parameter values of T1 and T2

Parameter (MOS)	Value	Parameter (BJT)	Value
LEVEL	1	IS	10^{-16}
VTO	4.83	BF(β)	10
KP	0.5	NE	2

Our study is concerned mainly with the changes in parameters β (forward current gain), K_p (MOS trans-conductance, and V_T (threshold voltage)[6]. Other factors are not significantly impacted by irradiation [2].

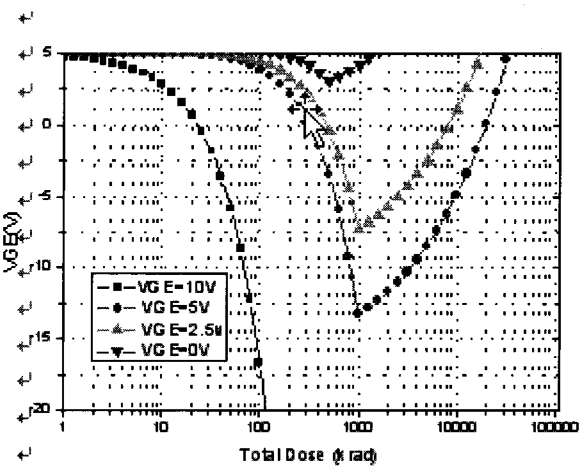
3.2 Comparison with Experimental Results

The experimental results of exposing IGBT samples to gamma radiation source show shifting of threshold voltages in the MOSFET[1,4] and degradation of carrier mobility and current gains. The collector current characteristics as a function of gate emitter voltage curves are analyzed with the model considering the radiation damage on the devices for different dose. At low total dose rate, the V_T shift is the major contribution of current increase, but for more than some total dose, the current is increased because of the current gain degradation occurred in the vertical PNP at the output of the IGBTs.

The change of V_{GE} is more or less rapid decrease for 0, 2.5, and 5 V, compared with that for 10 V since the depletion region under the gate oxide is expanded. It is estimated that the charge trapping occurs and the change of threshold voltage decreases as the depletion region increases. The decrease of current gain in bipolar transistor affects the increase of V_{GE} .The value of V_{GE} should be increased when the current gain in bipolar transistor decreases. The dominant effect seems to occur by charge trapping at the gate of MOSFET (T1). The effect is a decrease in the threshold voltage, and then an increase in T1 drain current. The result implies an increase in the base current of bipolar transistor T2. V_{GE} in T1 then should be lower to achieve the same collector current I_C for T2. The experimental results in Fig. 3.3 show that the slope of V_{GE} vs. total dose up to 30 krad is more rapid decrease as the value of gate bias voltage becomes larger, and satisfy the simulation ones.

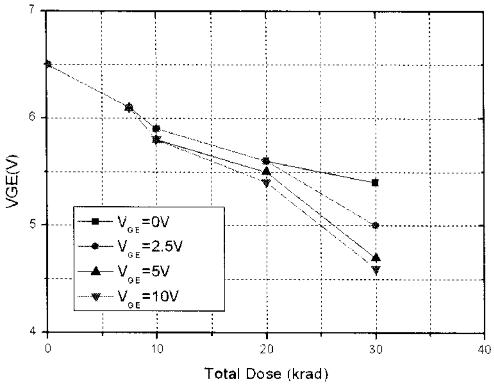
Table 3.2 Parameter Values of M_{β} and M_T for Positive Biases ($I_d = 100$ mA, $K_p = 0.5$, $\beta_{pre} = 10$, $V_T = 4.83$ V)

V_{GE} (V)	M_{β}	M_T
0	0.075	0.009
2.5	0.075	0.016
5	0.075	0.02
10	0.01	0.22

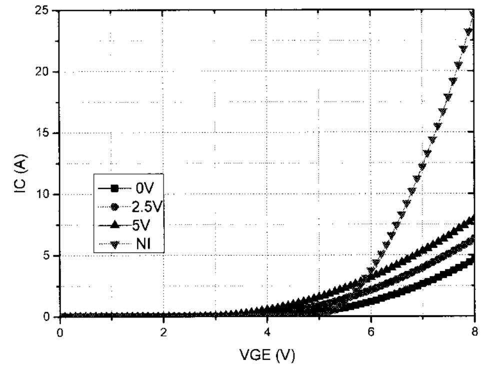


<Fig. 3.2> V_{GE} vs. total dose for Positive Biases at $I_D = 100$ mA

The characteristic is mainly affected due to two phenomena. One is an interface trap buildup in T1, and another is a drop in T2 current gain BF. The V_{GE} which include the effect of irradiation by modeling the V_T shift and current reduction under gamma irradiation is shown in Fig. 3.2 for positive gate bias under irradiation. We are interested in the current gain changes in transistor before and after irradiation, as a function of the bias values applied during this process.



<Fig. 3.3> An experimental result of V_{GE} vs. total dose up to 30 krad for Positive Biases at $I_D = 100$ mA



<Fig. 3.4> I_C vs. V_{GE} for pre-irradiation and post-irradiation under positive biases at 100krad

When the transistor operates in the saturation region, I_D is described as

$$I_D = \beta \cdot K_P (V_{GE} - V_T)^2 \qquad (3.1)$$

The β and V_T are variables to get I_D. The V_{GE} is obtained from eq. (3.1) as

$$VGE = V_T + \sqrt{\frac{I_D}{\beta_{post} \cdot K_P}} \qquad (3.2)$$

In eq. (3.2), V_T is computed as

$$V_T = V_{T0} - M_T \Phi \qquad (3.3)$$

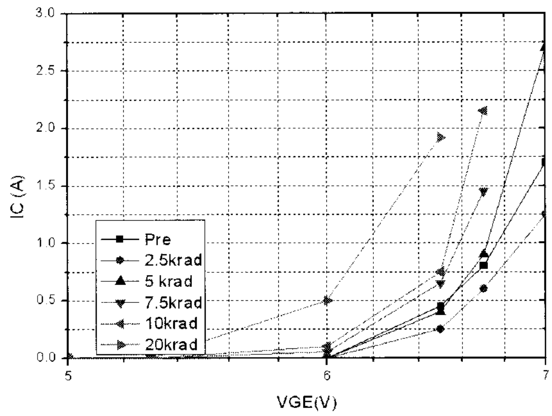
where V_{T0} is pre-irradiated threshold voltage, M_T is threshold reduction coefficient, and Φ is total dose irradiation.

The 1,200 V IGBTs (IRG4PG50S) has shown the relationship between the threshold voltage and the total dose of 0 to 30 Krad as $V_T = 4.36 - 0.06\Phi$[4]. The reduction of current gain for bipolar transistor has performed and M_β was found to be close to 1.5×10^{-4}[2].

Table 3.3 SPICE model parameter at the total dose 100krad for a negative gate bias

V_{GE}(V)	BP	V_T
−2.5	5	4.82
−5	5	4.58
−10	5	0.83

The SPICE model parameter for the IGBTs irradiated at 30 krad with the positive and negative gate bias is shown in Table 3.3. The dependence of the gate bias voltage on the V_T trend is shown for different V_{GE} voltages. The current gain, BP, shows constant because the PNP transistor formed at the substrate is independent of the gate bias at the top of the devices.



<Fig. 3.5> An experimental result of I_C vs. V_{GE} for pre-irradiation and post-irradiation up to 20 krad under positive bias of 5V

The positive biased IGBT shows a more dramatic reduction than negatively biased one with increasing dose[4]. The positive bias voltages induce an expansion of depletion region under gate oxide which results in increasing the possibility of capturing of negative charges at the gate oxide. It gives the reduction of V_T as well as the reduction of current gain, thus the slope of I_C curve is lowered. The negative biased one as gives a less severe V_T shift, and the reduction of current gain is a dominant factor to determine the current voltage characteristics.

The I_C's as a function of V_{GE} characteristics are shown in Fig. 3.4 and Fig. 3.5. Fig. 3.4 shows the simulation of pre-irradiation and post-irradiation, and Fig. 3.5 does the experimental results up to 20 krad under positive bias of 5V, respectively. The simulation ones represent that the slope become steeper as the bias voltage increases from 0 to 10 V. The experimental ones have the general phenomena that the I_C is sharply increases right after V_{GE} = 5 V, while the current keeps zero current when V_{GE} changes 0 to 4 V, which are satisfied with the simulations. In addition, As the total dose becomes bigger, the slope is steeper than the lower dose under the same bias voltage of 5V.

4. CONCLUSIONS

The results turned out to be successful. The experiment results are satisfied with the simulation ones to the some degree. Our simulations and experiments establish the basis for a test and an analysis for designing IGBT under the gamma radiation environment.

The SPICE model considering the change of model parameters of post-irradiated devices allows the engineers to design optimized circuits for the system circuits that are exposed to the radiation environments. It is found that the dominant factors are the threshold voltage reduction of MOS and the current gain of BJT. It is expected that the parameter values of M_β and M_T shown in Table 3.1 and 3.2 provide the design parameters.

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