Proceedings of the Korean Nuclear Society Spring Meeting
Kwangju, Korea, May 1997

Quality Degradation of Semiconductor Transistors by 1MeV Electron Beam Exposure

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Abstract

This paper presents preliminary results on the degradation of BJTs(Bipolar Junction Transistors) and MOSFETs(Metal Oxide Semiconductor Field Effect Transistors) by 1MeV electron beam. Exposure experimental results show that the change of minority-carrier life time in base region dominates the behavior of BJTs and that the buildup of charges in oxide region can affect the value of threshold voltage for MOSFETs. It was possible to correlate the decrease of the minority-carrier life time of BJTs with irradiation dose, while the shift of MOSFETs' threshold voltage was not only a function of charge buildup in oxide region.

1. Introduction

Because of the wide usage of electronic system in a radiation environment such as a nuclear power plant, a space satellite, an accelerator, and a medical application, a lot of studies on this topic have been established around the world since 1950s. Although the demands for radiation hardened semiconductors have increased years by years, no such a study has ever been carefully performed in KOREA. The following paragraphs offer a discussion of the degradation of BJTs and MOSFETs and the mechanisms describing the behavior of them in a radiation environment. A model for charge buildup in oxide region was able to describe the change of threshold voltage of MOSFETs.

2. Experimental

A total of 148 semiconductor transistors have been studied before and after exposures to several levels of dose from 0.5kGy to 100kGy of 1MeV electron beam by the linear accelerator in Samsung Electron beam Processing facility(SEP). The transfer characteristics of the BJTs and MOSFETs were obtained by using semiconductor parameter analyzer(HP4155A). The test matrix and the experimental setup are shown in Table I and Figure 1, respectively. All of the typical values shown in Table I are average values before irradiation. During exposure every terminal of transistor was kept together to a ground potential relative to electron beam. All the measurements of parameters of semiconductors were performed at room temperature.

Table I. The Test Matrix

		Typical value		Definition
		2N3904	2N3906	
BJT	h_{FE}	170	170	I_C/I_B : dc current gain
	BVceo	2.6V	-2.6V	breakdown voltage at I_B = 0A
	Vbe_on	0.65V	-0.68V	turn-on voltage at I_C-Vbe curve
	Go	$0.5m\Omega^{-1}$	$0.9m\Omega^{-1}$	$1/r_O$: output conductance
MOSFET (4007CMOS)		n-channel	p-channel	
	V_{TH}	1.5V	-1.5V	threshold voltage
	Gm	$1\ m\Omega^{-1}$	$0.5\ m\Omega^{-1}$	transconductance
	BVdso	2.1V	-2.1V	breakdown voltage where Vg = 0V
	Go	$0.01\ m\Omega^{-1}$	$0.1\ m\Omega^{-1}$	$1/r_O$: output conductance

All of the specimens were irradiated by 0.5, 1, 10, 50, 100kGy electron beams of 1MeV energy.

3. Transistor Parameter Models

The most important parameters of BJT and MOSFET are h_{FE} and V_{TH}, respectively. Therefore the discussion of them is now established as following.

3.1 Current Gain of BJTs

For application of analog amplifiers, a high value of h_{FE} of BJT is needed. So the decrease of this value by irradiation results in serious degradation of performance of amplifier circuits. The current gain h_{FE} of BJT is given by[1] :

$$h_{FE} = \frac{1}{\frac{W_B}{2\tau_B \cdot D_n} + \frac{D_P}{D_n} \cdot \frac{W_B}{L_p} \cdot \frac{N_A}{N_D}} \tag{1}$$

where

W_B is the width of the base,

τ_B is the minority-carrier lifetime in the base,

L_P is the diffusion length for holes in the emitter,

N_A and N_B are the acceptor and donor atom concentration, respectively,

D_P and D_n are the diffusion constants for holes and for electrons, respectively.

All of the parameters in equation (1) are affected by irradiation but the dominant parameter is minority- carrier life time τ_B. From equation (1), a relation between h_{FE} and τ_B can be derived as

$$\Delta(\frac{1}{h_{FE}}) \propto \Delta(\frac{1}{\tau_B}). \tag{2}$$

3.2 Threshold Voltage of MOSFETs

The stability of the threshold voltage V_{TH} for MOSFETs must be obtained for a stable operation of any electronic circuits using MOSFETs. The threshold voltage is the voltage necessary for making the conduction channel in the semiconductor region just beneath the gate oxide. V_{TH} is generally expressed as the following equation (3)[1]:

$$V_{TH} = \varphi_{MS} + 2\varphi_f - \frac{Q_{BO}}{C_{OX}} - \frac{Q_{tot}}{C_{OX}} \tag{3}$$

where

φ_{MS} is the metal-semiconductor work-function difference,

φ_f is the Fermi level,

Q_{BO} is the depletion charge by inversion,

Q_{tot} is the fixed charge in the oxide region,

C_{OX} is the capacitance of oxide.

4. Results and Discussion

The typical characteristic curves for BJT and MOSFET before and after irradiation are shown in figure 2(a) and (b), respectively. It has been found that the current gain of BJT decreases as the exposure level of dose increases and the change of the reciprocal value of h_{FE} is proportional to the exposure dose as shown in figure 3. Therefore from the equation (2), it is shown that the minority-carrier life time τ_B decreases as the exposure dose increases and the damage constant K_τ can be defined as following equation (4):

$$\Delta(\frac{1}{\tau_B}) \propto \Delta(\frac{1}{h_{FE}}) = \frac{\phi}{K_\tau} \tag{4}$$

where

ϕ is the exposure dose of the electron beam in kGy,

K_τ is the damage constant in kGy.

The irradiation of high energy electron beam can make the recombination centers in bulk of base region[2]. Higher the exposure dose, more the recombination centers is made in the base region so that the minority-carrier life time τ_B becomes shorter than that before irradiation.

It has been found that the h_{FE} of PNP BJT degrades less than that of NPN one. Since the damage constant K_τ of PNP is larger than that of NPN. The damage constant K_τ can be thought as a resistance to irradiation.

It has been found that the I_D-V_{GS} curves both for the n-channel and the p-channel MOSFET are shifted to the left direction as a result of irradiation. So the absolute value of V_{TH} decreased for the n-channel MOSFET and increased for the p-channel one.

The irradiation of electron beam on MOSFETs can cause an increase of charges in oxide region[3]. These charges affect on making of the conduction channel beneath the oxide region. The buildup charge is the immobile positive charge so that the p-type substrate beneath the oxide region is converted into n-type one and the n-type substrate becomes more n-type one[4]. A model of charge-buildup in the oxide region is shown in figure 4. The buildup charge ΔQ_{tot} can be calculated from

$$\Delta Q_{tot} = C_{OX} \Delta V_{TH} . \qquad (5)$$

In viewing figure 5, ΔV_{TH} of p-channel MOSFET is proportional to dose but not for n-channel one[5]. A reason for this is that the displacement damage is also produced in the bulk substrate. Therefore in the equation (5) the ΔV_{TH} is not only a function of ΔQ_{tot} but also that of atomic displacements occurring in the substrate.

5. Conclusion

The dependence of the current gain h_{FE} of BJT and the threshold voltage V_{TH} of MOSFET upon irradiation level of electron beam has been measured experimentally. A simple model presented to explain the results appears qualitatively correct. The decrease in h_{FE} as a function of exposure dose is greater for NPN BJTs than for PNP BJTs. The damage constant K_{τ} may be regarded as a 'resistance' to radiation exposure. The amount of the change of V_{TH} as a function of exposure level is less for n-channel MOSFETs than for p-channel MOSFETs. It has been found that the change of V_{TH} for n-channel MOSFETs was not only a function of charge buildup since at high exposure dose the displacement damage can be produced in the substrate. Clearly, a further investigation of this aspect is required.

Acknowledgment

We gratefully acknowledge the assistance of Duckyung Kim in SHI(Samsung Heavy Industry Co.) for performing of the electron beam exposure on our samples.

References

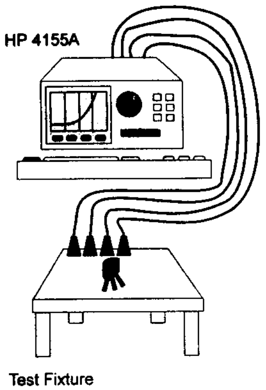
[1] Paul R. Gray and Robert G. Meyer, *Analysis and Design of Analog Integrated Circuits*, John Wiley & Sons Inc., p. 15, p. 62 (1993)

[2] W. E. Horne and R. R. Brown, "Correlation of Electron-Induced Changes in Transistor Gain with Components of Recombination Current", IEEE Trans. on Nucl. Sci., Vol. NS-13, No.6, p. 181 (1966)

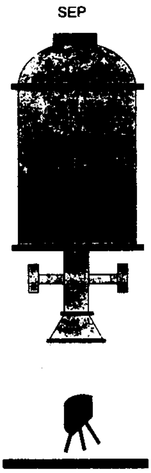
[3] A. I. Barry and D. F. Page, "Radiation Hardening of MOS Transistors for Low Ionizing Dose Levels", IEEE Trans. on Nucl. Sci., Vol. NS-13, No. 6, p. 255 (1966)

[4] H. I. Hughes, "Surface Effects of Space Radiation on Silicon Devices", IEEE Trans. on Nucl. Sci., Vol. NS-12, No. 6, p. 53 (1965)

[5] Roger Freeman, "A Simple Model for Predicting Radiation Effects in MOS Devices", IEEE Trans. on Nucl. Sci., Vol. NS-23, No. 6, p. 1216 (1978)



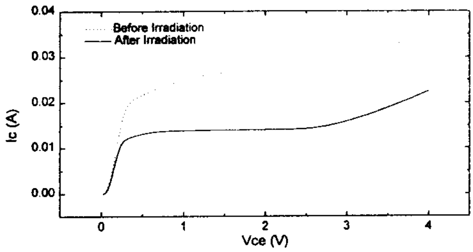
(a) test setup



(b) exposure setup

Figure 1. Experimental Setup

(a)



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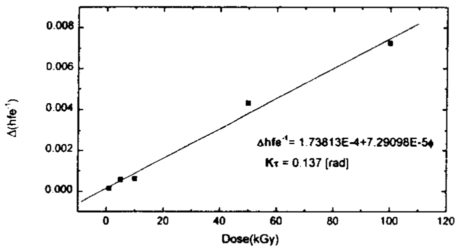

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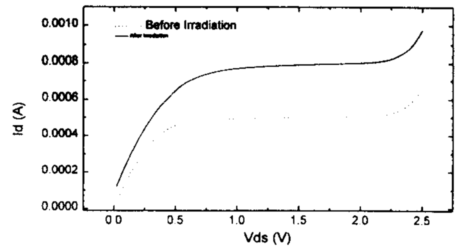

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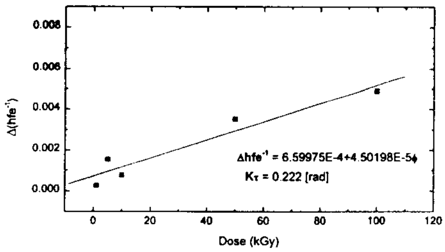

Figure 2. Transistor characteristic curves before and after irradiation (a) for NPN BJT and (b) for n-channel MOSFETs.

Figure 3. Electron-beam-induced change in reciprocal current gain (a) for NPN BJT(2n3904) and (b) for PNP BJT(2n3906). These data yield a damage constant K_{τ}..

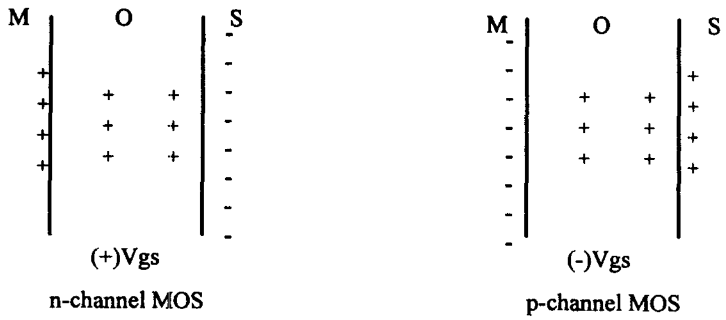

Figure 4. A model of charge buildup in MOSFET's gate oxide.

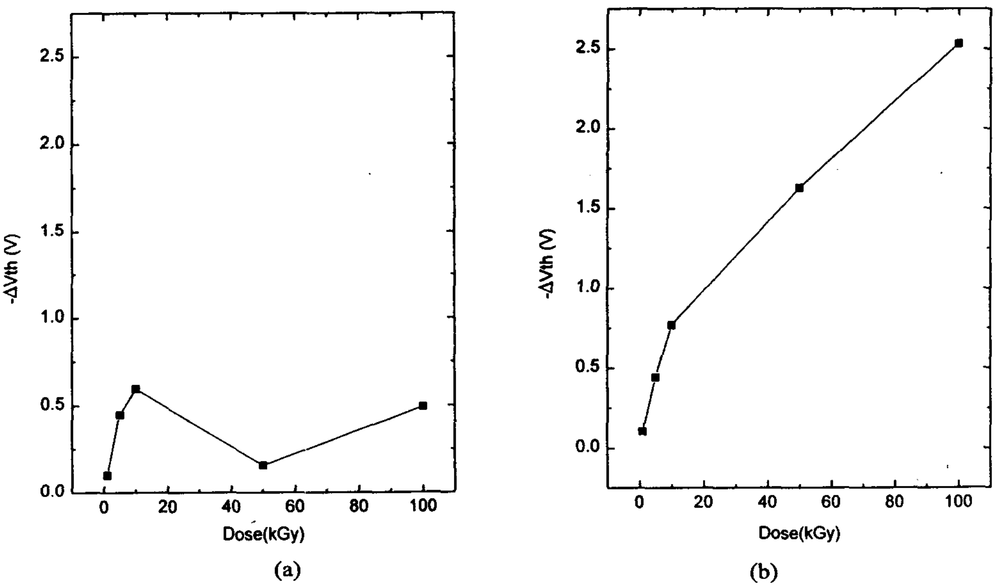

Figure 5. An experimental plot of ΔV_{TH} versus electron beam dose (a) for n-channel MOSFET and (b) for p-channel MOSFET.