Radiation Effects on the Power MOSFET for Space Applications

Young Hwan Lho and Ki Yup Kim

ABSTRACT—The electrical characteristics of solid state devices such as the bipolar junction transistor (BJT), metal-oxide semiconductor field-effect transistor (MOSFET), and other active devices are altered by impinging photon radiation and temperature in the space environment. In this paper, the threshold voltage, the breakdown voltage, and the on-resistance for two kinds of MOSFETs (200 V and 100 V of V_{DSS}) are tested for γ-irradiation and compared with the electrical specifications under the pre- and post-irradiation low dose rates of 4.97 and 9.55 rad/s as well as at a maximum total dose of 30 krad. In our experiment, the γ-radiation facility using a low dose, available at Korea Atomic Energy Research Institute (KAERI), has been applied on two commercially available International Rectifier (IR) products, IRFP250 and IRF540.

Keywords—Radiation effect, MOSFET, threshold voltage, breakdown voltage, dose rate, total dose, γ-radiation.

I. 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 40 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 for space and defense usages. The researchers in these countries have been sharing many reports leading to exchanges of satellite technology. However, the level of such technology in Korea is far behind, and it is time that a concentrated effort be made to change this.

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The types of radiation are generally divided into particle radiation and photon radiation. Particle radiation consists of charged particles such as protons, electrons, α particles, ions, and neutral particles, neutrons. Particle radiation may also induce ionization so that excess carriers are generated within a semiconductor device and material. Photon radiation consists of γ rays and/or x-rays. The unit primarily used in radiation effects that deal with ionization induced by γ rays is *rad*. A 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-s) and fluence (number/cm^2).

Commercial devices often have a channel stopper or guardband to provide isolation between adjacent devices. However, the threshold voltage of this region is usually not sufficient to prevent inversion in a radiation environment, and the guardband must be doped heavily enough to prevent inversion after irradiation and must be designed such that the gate oxide extends over the guard between the source and drain.

The gate voltage V_{GS}, required to make an inversion layer below the SiO_2, is called threshold voltage V_{th} and can be represented [1] as

$$V_{th} = \Phi_{ms} + 2\Phi_f - Q_{BO}/C_{ox} - Q_{tot}/C_{ox}, \quad (1)$$

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 charge in the SiO_2, and C_{ox} is the capacitance of the SiO_2.

A simple method for estimating the threshold voltage shift [2] due to the ionizing irradiation of a low dose rate was recently proposed for power metal-oxide semiconductor field-effect transistors (MOSFETs). Briefly, the method consists of estimating the threshold voltage shift by the oxide charge trapping at the gate oxide immediately after irradiation and annealing at 100°C. The minimum requirement of the gate threshold voltage, denoted by V_{th}, is 2 V.

The breakdown voltage [3] between drain and source with the gate short-circuited to the source, denoted by BV_{DSS}, is the lowest voltage that prevents an avalanche across the termination ring. An avalanche occurs at a lower value of V_{DS} whenever the channel is turned on at $V_{GS} = 0$. The breakdown voltages of the International Rectifier (IR) products we have tested should be 200 V.

In response to a small applied voltage V_{DS} , the n-type bar acts as a simple semiconductor resistor. The current I_D increases linearly with V_{DS}. As the current increases, the ohmic voltage drop along the n-type channel region reverse-biases the gate junction, and the conducting portion of the channel begins to be established. The I-V characteristics [4] for very small V_{DS} show that the MOSFET acts like a variable resistance whose value depends on V_{GS}. The ratio V_{DS}/I_D at the region is called the on-resistance R_{DSON}. The parameter R_{DSON} is important in switching applications that use a few ohms. The ideal switch has 0 ohms. The maximum on-resistance requirement of the product is 85 mΩ.

II. Radiation Effects on Power MOSFET

MOS devices are among the most sensitive of all semiconductors to radiation, in particular ionizing radiation, showing much change even after a relatively low dose. The effects of radiation on two different MOSFET devices are compared for the same level of total dose. The gate oxide structures give the main influence on the changes in the electrical characteristics [2] affected by irradiation. A change of the I-V characteristic towards more negative values of the gate voltage is brought by a charge trapping at the gate oxide. This is very 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.

After differentiation of (1), we can obtain a relation between threshold voltage V_{th} and charge Q_{tot} in SiO_2:

$$\Delta Q_{tot} = -C_{ox}\,\Delta V_{th}\,, \tag{2}$$

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

The charge Q_{tot} is influenced by fixed oxide charge Q_F and interfacial trap charge Q_I as shown in (3).

$$\Delta Q_F - \Delta Q_I = -C_{ox}\Delta V_{th} \tag{3}$$

When the oxide is irradiated, a greater number of dangling bonds are created. The dangling bonds in SiO_2 near the interface between Si and SiO_2 will trap charge Q_I, and this charge is negative for an n-channel MOS because the sign of voltage V_{GS} applied at the gate is opposite for a MOSFET.

Fixed oxide charge Q_F is deposited in oxide defects by capturing holes generated by irradiation. Owing to the very low mobility of a hole relative to an electron in SiO_2, a hole is easily captured in defects and accumulates a positive charge for an n-channel MOS. Then, the fixed charge makes the threshold voltage a more negative value for a MOSFET. The fixed oxide charge is more dominantly affected by radiation than the interfacial trap charge, which is almost the same in different MOSFETs.

In order to improve the electrical characteristics of a breakdown voltage, a termination technique using a field limiting ring structure has been widely used to obtain the ideal breakdown of a plane junction. The field limiting ring contributes to reduce the effect of radiation through utilizing the junction curvature on the breakdown voltage in the planar devices [5].

On-resistance is obtained from the slope of I_D vs. V_{DS}. When the slope is steeper, it indicates that the MOSFET has a better characteristic, which is a less resistance value. The static drain to source on-resistance is not affected due to the low dose [6].

III. Experimental Results

Two kinds of commercial grade IR MOSFETs (200 V and 100 V of V_{DSS}) are chosen as the tested parts. The threshold voltage and breakdown voltage (BV_{DSS}) are tested and compared with the specifications under pre-irradiation and post-irradiation of low dose rates of 4.97 and 9.55 rad/s, and a maximum total dose of 30 krad. The test procedure and method is carried out using Mil-Std-883 Method 1019. The γ source using ^{60}Co is used for the test of commercial IR MOSFET products. A sample size of five pieces is used for each test.

Figures 1 to 5 show the threshold voltage, breakdown voltage, and on-resistance characteristics of irradiated MOSFETs based on the quantity of dose and after annealing at 100°C for 168 hours. The total doses are 0, 5, 10, 15, 20, and 30 krad, respectively, and the dose rate is either 9.55 or 4.97 rad/s. The annealing at 100°C for 168 hours is carried out right after irradiation.

As shown in Fig. 1, the threshold voltage V_{th} of the 200 V MOSFET decreases as the quantity of the total dose is increased up to 30 krad with a dose rate of 9.55 rad/s; however, the voltage does not recover after annealing at 100°C for 168 hours.

Figure 2 shows that with a dose rate of 4.97 rad/s the voltage recovers to 1.9 V—the same level as the voltage at 20 krad irradiation—after annealing at 100°C for 168 hours; however, this does not satisfy the minimum threshold voltage requirement of 2.0 V [7].

The slope of the threshold voltage shown in Fig. 3 for the dose rate of 4.97 rad/s for the 100 V MOSFET is less steep than that of the 200 V MOSFET shown in Fig. 2, which is due to the thickness of the gate oxide. As a result, it satisfies the minimum threshold voltage requirement. The descent rate of threshold voltage ΔV_{th} of the 200 V and 100 V MOSFETs can be seen in Tables 1 and 2, respectively. The test data satisfy (2).

The breakdown voltage characteristics [5] are shown in Fig. 4, and the results meet the specification of a minimum 200 V. It is evident from this figure that the breakdown voltage remains unchanged for the irradiation and even after annealing. It is expected that the field limit ring for achieving a breakdown

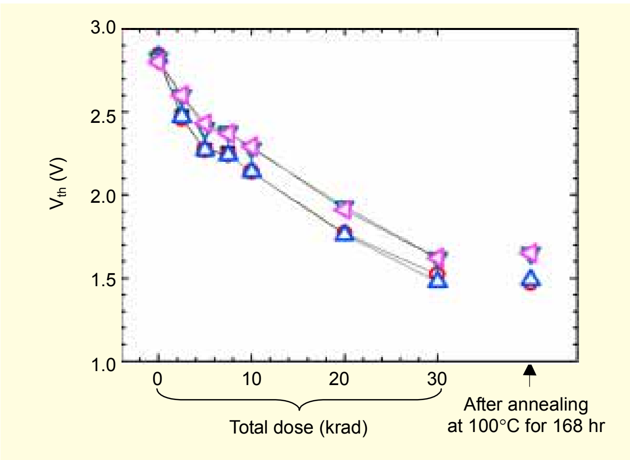

Fig. 1. Threshold voltage (V_{th}) characteristics of a MOSFET (200 V) under a dose rate of 9.55 rad/s.

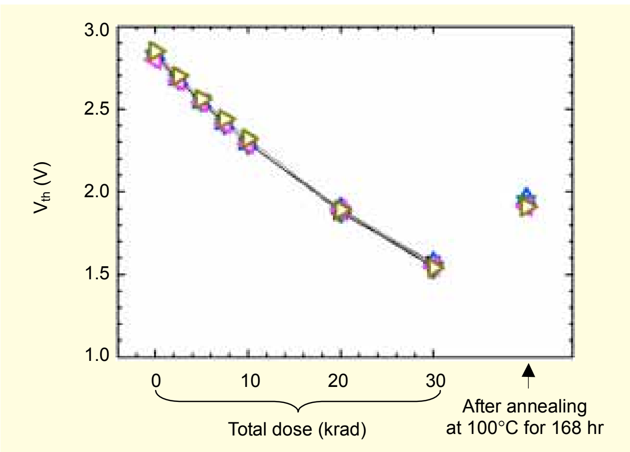

Fig. 2. Threshold voltage characteristics of a MOSFET (200 V) under a dose rate of 4.97 rad/s.

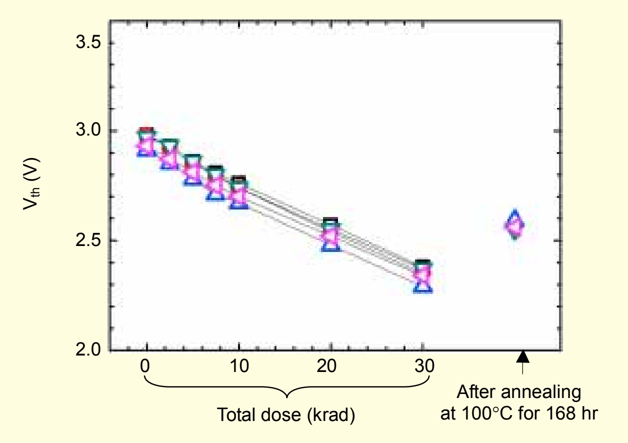

Fig. 3. Threshold voltage characteristics of a MOSFET (100 V) under a dose rate of 4.97 rad/s.

Table 1. Threshold voltage and change of threshold voltage of a MOSFET (200 V) as the total dose increases.

Total dose (krad)	0	2.5	5	7.5	10	20	30
V_{th} (V)	2.82	2.68	2.55	2.42	2.3	1.87	1.57
ΔV_{th}		-0.14	-0.13	-0.13	-0.12	-0.43	-0.30

Table 2. Threshold voltage and change of threshold voltage of a MOSFET (100 V) as the total dose increases.

Total dose (krad)	0	2.5	5	7.5	10	20	30
V_{th} (V)	2.98	2.93	2.86	2.81	2.76	2.57	2.38
ΔV_{th}		-0.05	-0.07	-0.05	-0.05	-0.19	-0.19

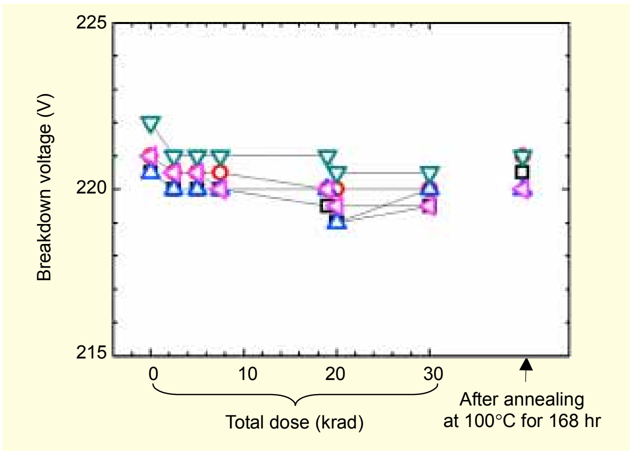

Fig. 4. Breakdown voltage characteristics of a MOSFET (200 V) under a dose rate of 4.97 rad/s.

voltage of the sample device has a wide enough margin for the charge accumulation occurring at the oxide of the termination when the device is exposed to the radiation source.

The on-resistance characteristics are shown in Fig. 5, and the results satisfy the requirement of a maximum 85 mΩ [7].

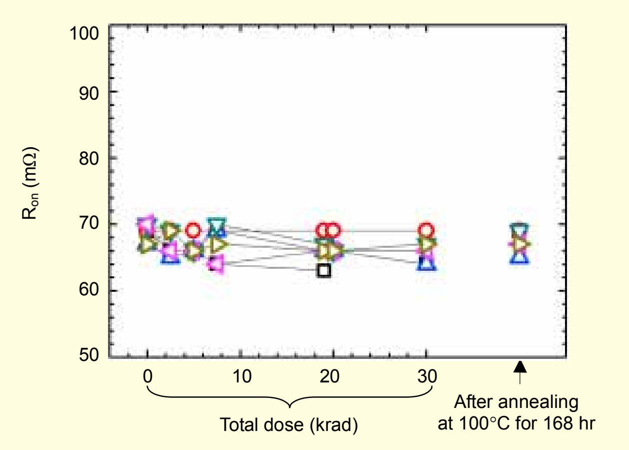

Fig. 5. On-resistance characteristics of a MOSFET (200 V) based on the quantity of dose and after annealing at 100°C for 168 hours.

IV. Conclusion

The breakdown voltage does not change significantly with respect to the dose rate and total dose. Our experiment shows that IR commercial products satisfy the specifications of the breakdown voltages of 100 and 200 V. The on-resistance is not affected by the dose in the test. Our two experiments show that IR commercial products are robust when exposed to radiation. When we apply radiation, the slope descent rate of the threshold voltage reduces linearly as the total dose increases. Here, we observe that the descent rate is an increasing function of the threshold voltage. Both devices recover back the original specification except for the 200 V MOSFET for a dose rate of 9.55 rad/s after the annealing is finished. No permanent damage has occurred. The threshold voltage for a high dose beyond 20 krad and a 200 V MOSFET did not meet the minimum requirement of 2.0 V. Thus, we suggest that the device manufacturers make a note of this point while designing a new structure to prevent the shift of threshold voltage for a higher dose rate.

References

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

[2] Jim Schwank, "Total Dose Effects in MOS Devices," *IEEE Nuclear Space Radiation Effects Conf.*, Short Course III-47, July 2002.

[3] Won-So Son, Sang-Gi Kim, Young-Ho Sohn, and Sie-Young Choi, "A New SOI LDMOSFET Structure with a Trench in the Drift Region for a PDP Scan Driver IC," *ETRI J.*, vol. 26, no. 1, Feb. 2004.

[4] Jacob Milman and Arvin Grabel, *Microelectronics*, McGraw-Hill Int'l ed., pp. 138-1987.

[5] S.Y.Lee, Y.H.Lho, and J.D. Kim, "On the Design of Field Limiting Ring for Improving Corner Breakdown Voltage," *Proc. PEMC '98*, Prague, Czech, 1998, pp. 41-44.

[6] T. P. Ma and Paul V. Dressendorfer, *Ionizing Radiation Effects in MOS Devices and Circuits*, John Wiley & Sons, 1989.

[7] International Rectifier, *200 V N-Channel MOSFET,* IRFP250 Datasheet, May 2001.