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Evaluation of Electrical Characteristics of MOSFET for Electron Beam Induced Effects

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Abstract: ***The space environment is hostile to most semiconductor electronic devices and components used for space applications and hence it is essential to assess the extent of radiation induced degradation in electrical characteristics of devices planned and used for space applications. Especially, the Van Allen Belts consist of high energy electrons which are in continuous motion. Satellites systems operating in Low Earth Orbits (LEO) are prone to get exposed to high energy electrons. This paper describes the effect of electron beam irradiation on MOSFETs planned for space applications. The devices selected for the study are 2N6768 n-channel MOSFETs (JANTXV) procured from ISAC, Bangalore. The decapped MOSFETS are exposed to a beam of electrons for various doses ranging from 50 Gy to 10 kGy in the electron energy range 7 - 10 MeV using the electron accelerator facility at RRCAT, Indore. Pre and post-irradiation measurements of the electrical characteristics are undertaken to investigate the electron induced device degradation and damage. The investigation reveals that there is a substantial increase in the leakage current and the transconductance also displays considerable reduction upon exposure to electron beam. These changes may be attributed to the trapped electron-holes pair in the gate oxide and Si/SiO$_2$ interface. The increase in the leakage current can have significant effect on the device performance in a radiation environment.***

Keywords: MOSFET, Radiation, Dose, Leakage current

1. Introduction

The radiation generally encountered in space includes γ-rays, X-rays, energetic electrons, protons, light ions and heavy ions of different flux and energy. Semiconductor devices exposed to these radiations may undergo severe degradation and damage. The damage or degradation may be permanent or transient. The degradation behaviour is a complex process and is dependent not only on the nature of the device but also on the radiation characteristics viz., dose, dose rate, species and the energy of radiation. The study of the effect of ionizing radiation on semiconductor devices has thus become very important to have an understanding of the physical mechanism of the damage process and to assess the device performance when they need to be operated in the radiation environment.

Excellent literature is available on effects of radiation viz., γ-rays, neutrons, electrons, protons, heavy ions on variety of semiconductor devices including Bipolar Junction Transistors (BJT's), integrated devices and Complimentary MOS (CMOS) devices. However, the basic mechanism of radiation-semiconductor interaction leading to device degradation is not yet completely understood. While the study of radiation induced effects in CMOS and IC's is more complex, the study on 3-terminal semiconductor device (BJT/ MOSFET) can provide useful insight into the mechanism of degradation [1]. Many of the BJTs and MOSFETs which are not available in radhard (radiation hardened) version, are still being used in space systems. It is therefore essential to characterize these devices for radiation induced effects. Further, investigations on radiation-induced effects on devices indigenously made in India, to our knowledge, have not been fully carried out. It is thus important to establish radiation-induced response of these devices in comparison to other vendor's parts of the similar family.

The metal oxide field effect transistor (MOSFET) is an important device in microprocessors, memory circuits, ICs and mainframe computers of space systems. While BJT is extensively studied for radiation induced effects, there appears to be rather limited work on MOSFETS. Further, it is known that radiation damage mechanism in MOS devices is quite different from that in BJTs and hence it is essential to understand the basic mechanism of device degradation and damage in MOS structures. Electrons of energy greater than 200 keV is capable of providing sufficient energy to displace silicon atom. Thus, the dominant mechanism of the interaction of the electrons with semiconductors is to produce atomic displacement which can have serious impact on electrical characteristics. MOS (Metal oxide semiconductor) devices are the most sensitive of all semiconductor devices to radiation showing considerable degradation even for a relatively low dose of exposure to high energy electrons. In the present research work, we have undertaken the investigation of the effect of exposure of MOSFET to a beam of electrons to assess the extent of possible degradation in the electrical characteristics.

2. Materials and Methods

The MOSFETs selected for the present study are planned for space applications by ISRO Satellite Centre (ISAC, Bangalore). The devices selected are 2N6768 n- channel MOSFETs (JANTXV) procured from component division of ISAC. Eight devices (all with same date code) are collected and pre- irradiation measurements of electrical characteristics viz., threshold drain to source voltage (V_{DS}), leakage current (I_D), forward and reverse resistances, output characteristics, transfer characteristics and source to drain diode characteristics are measured using TESEC semiconductor measurement system in the component division of ISAC, Bangalore. These devices belong to the same family and batch code and their electrical behaviour are also very much identical. One device is kept as the control device and the rest seven devices are numbered and decapped for the exposure of electron irradiation. The decapped MOSFETs are exposed to a beam of electrons for various irradiation dosages at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. The linear electron accelerator operational at RRCAT, generates electrons in the energy range of 7MeV – 10MeV at a controllable power level up to 3kW. The process parameters of the electron irradiation facility can be optimized to meet the required dose rates. The electron beam for irradiation has a beam current of 285mA, pulse repetition rate of 5Hz with pulse width 10 µs. Irradiation is performed by dual scattering between two Aluminium plates of thickness 2mm each. The optimized dose rate is 10Gy per second. Precise dose measurements are possible by using Bruker EPR dosimetry system. The de-capped devices are exposed to different doses viz., 50Gy, 100Gy, 200Gy, 500 Gy, 1 kGy, 5 kGy and 10 kGy respectively. The post irradiation measurements of electrical characteristics are performed at ISAC.

3. Result and Discussions

The MOS consists of three layers namely, metal, oxide and semiconductor. The effects of radiation are severe in the oxide (SiO_2) and at interfaces (Si/SiO_2) [2].Electron beam of high energy can produce both ionization and displacement effects. The threshold voltages, current drives and leakage currents of MOSFET change due to a change in number of factors.

3.1 Shift in the threshold voltage

When the electrons pass through the gate oxide of a MOSFET, the energy deposited by the electron generates electron- hole pairs. The electrons and holes are transported by the electric field, but since electron possess higher mobility than holes in the SiO_2, the latter drift slowly and are trapped in the gate oxide. For positive voltage, holes move to the Si-SiO_2 interface side and are trapped. Conversely for a negative gate voltage, holes move to the metal side and get trapped. In the absence of electric field under zero gate voltage, the holes diffuse isotropically [3]. The Sub-threshold I-V characteristics of n-channel 2N6768 for various irradiation dosage is shown in Figure 1.

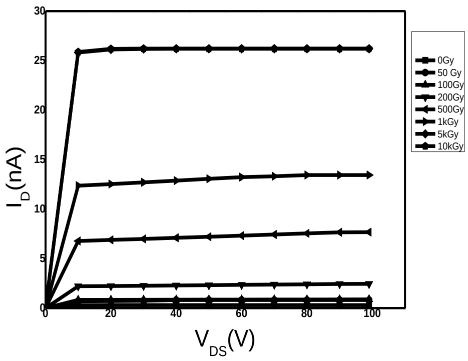

Figure 1: Output Characteristics- Drain current vs Drain to Source Voltage for different doses

As seen in the plot, the drain current (I_D) increases as the electron dose increases for a given value of drain to source voltage (V_{DS}). This increase in the drain current may be attributed to the change in gate threshold voltage of MOSFET.

For n-channel power MOSFET, the threshold voltage becomes negative due to radiation induced positive charges dominating in the oxide traps. These shifts are caused by the positive oxide traps and interface traps. MOSFET operates under strong inversion where the gate bias is much larger than threshold voltage of the device. The threshold voltage shift is given by

$$\Delta V_{TH} = \left(\frac{q}{C_{ox}}\right) \Delta N_{it} \quad (1)$$

where q is the charge, N_{it} is the change in electron-hole pair concentration and C_{OX} is the capacitance per unit area. ΔN_{it} depends on the number of electron hole pairs produced per dose, probability of electron hole recombination, energy of incident electron and the number of interface trapped charges [4]. The Gate threshold voltage decreases as the dosage increases as represented in the Figure 2. It is known that the traps above mid gap are acceptor like and those below are donor like. In n-channel MOSFET, the acceptor like traps which are below the Fermi level are negatively charged and the threshold voltage shift will be positive i.e., the threshold voltage decreases.

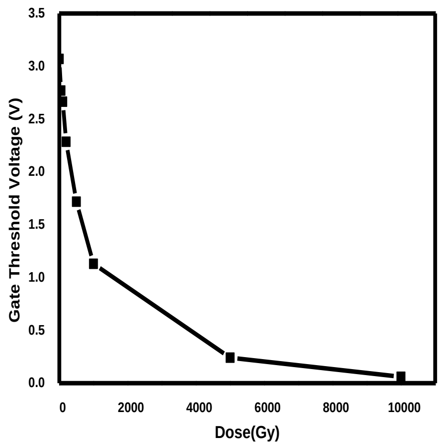

Figure 2: Variation of Gate threshold voltage as with electron dose

3.2 Variation in leakage current

The OFF-state current in MOSFET is the current which flows from drain to source when gate to source voltage is zero and is referred as the leakage current. The leakage current is measured as a function of dose and is shown in the figure 3.

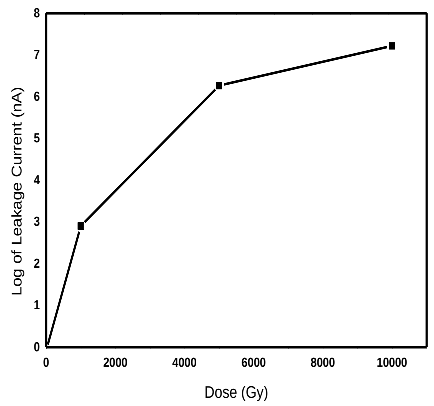

Figure 3: Variation of leakage current with electron dose

It is seen that the leakage current increases as the accumulated electron dose increases. This increase in leakage current is caused by the decrease in the gate threshold voltage. The increase in leakage current can be critical when the transistor is used as a switch. Figure 4 shows the variation in the ON-state drain current with drain to source voltage for various electron doses. It is observed from the plot that ON-state I_D saturates quickly at lower V_{DS} as the electron dose increases.

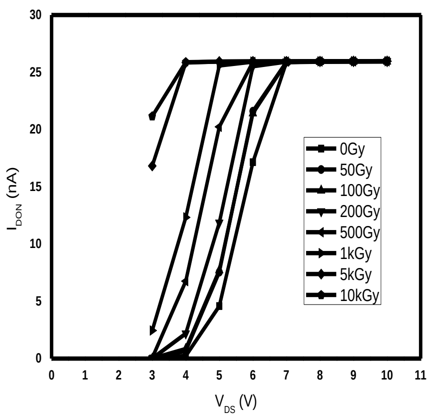

Figure 4: Transfer characteristics- Variation of ON-state drain current with drain to source voltage for various electron dose.

3.3 Decrease of mobility and transconductance

The change in the mobility of charge carriers (electrons) due to electron beam irradiation is related to increase of interface traps, since the conductivity of a MOS transistor is due to carrier motion close to silicon oxide interface. The post-irradiation mobility (μ) of electrons can be expressed by the following empirical formula

$$\mu = \frac{\mu_o}{1+\alpha(\Delta N_{it})} \quad (2)$$

where μ_o is pre-irradiation mobility, ΔN_{it} is the change in electron-hole pair concentration (interface traps) and α is a parameter whose value depend on the technology of device manufacturing. Since the transconductance (g_m) of the device is proportional to electron mobility in the linear region [5], a change in mobility will result in a corresponding change in g_m. Figure 5 shows the measured transconductance of the MOSFET as a function of accumulated electron dose.

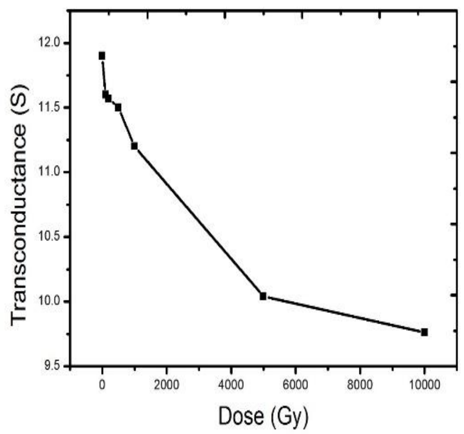

Figure 5: Variation of transconductance of MOSFET with electron dose

It is evident that the transconductance decreases as the electron dose increases. This would mean that the driving capability of the device decreases as the MOSFET is exposed to higher electron doses.

4. Conclusion

The power MOSFET 2N6768 planned for space applications is vulnerable to high energy electrons induced effects. The increase in the leakage current of the device with electron dose may be critical when the transistor is used as a switch. The decrease in the transconductance of the device at higher electron doses could affect the driving capacity of the device. Thus, care must be exercised while employing this family of MOSFETs in a radiation environment.

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