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Electron Irradiation on Metal Oxide Silicon Field Effect Transistors in Space Applications

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ABSTRACT

The space environment is hostile to most semiconductor electronic devices and components used for space applications. The radiation generally encountered in space are α, β, γ, x-ray, energetic electrons, protons, neutrons and ions of various kinds. 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 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. The energy dissipated by electrons in semiconductors is sufficient to displace silicon atoms and causes a shift in the threshold voltage and leakage current. The study indicates that the gate threshold voltage substantially decreases with the increase in electron dose. The leakage current increases with dose which could have an impact on the performance of the device. The transconductance of the MOS transistor is found to decrease with increase in electron dose. The observed changes in the electrical characteristics upon electron irradiation are analysed and interpreted as due to trapped charges in the SiO_2 layer and at the interface. The present investigation reveals that there is a remarkable degradation in threshold voltage and the leakage current displays substantial increase when the devices are exposed to electrons. This increase in leakage current can have significant impact on device performance in a radiation environment.

INTRODUCTION

The study of radiation induced effects on semiconductor devices has emerged .as .an active field of research in the last few decades and various space agencies around the world are engaged in R and D in this field. When semiconductor electronic devices are exposed to radiation (viz. γ-rays, X-ray, electrons, .neutrons, protons or heavy ions, etc.) they may undergo severe degradation. 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. Further, compared to BJTs rather little literature is available on radiation damage studies in MOS devices and therefore we have taken up the study of MOSFETs for radiation testing. 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.

MATERIALS AND METHODS

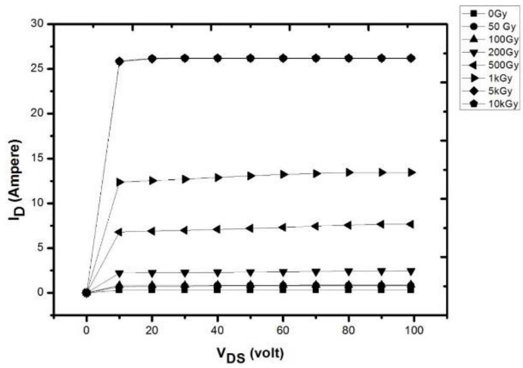
The metal oxide field effect transistor (MOSFET) is an important device in microprocessors, memory circuits, ICs and mainframe computers of space systems. However, there appears to be rather little studies on radiation induced parametric degradation of MOSFETs. Such radiation response data and radiation tolerance assessment is quite important especially when the devices need to be operated in a radiation rich environment such as in space. Hence in collaboration with scientists and engineers of ISRO Satellite Centre (ISAC, Bangalore), we have undertaken a program to study the radiation induced effects in some selected MOSFETs which are being used for space applications. 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 ISRO 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 dosage. These decapped devices are exposed to electron irradiation at the electron irradiation facility available in Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, Madhya Pradesh. The experimental irradiation facility based on radio frequency linear electron accelerator is operational at RRCAT. The accelerator is operated in the energy range 7MeV – 10MeV at a controllable power level up to 3kW. The process parameters of the facility have been optimised 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 10microsecond. Irradiation happens by dual scattering between two Aluminium plates of thickness 2mm each. The dose rate is 10Gy per second.

Alanine EPR dosimetry system is used. Stable free radicals are formed in alanine (a tissue equivalent material) when exposed to ionizing radiation [2]. Concentration of the free radicals is proportional to the radiation dose received by alanine, which is measured off line by Electron Paramagnetic Resonance (EPR) spectrometer as the peak to peak height of the central line in the spectrum. The Alanine dosimeters are less sensitive to environmental condition, possess wide dynamic range 50-10^6 Gy and less fading rate makes these detectors versatile for dose measurements. Bruker Germany make EPR dosimetry system having calibration traceability to NPL, UK is used for precise dose measurements. The de-capped devices are exposed to for a range of dosage of 50Gy, 100Gy, 200Gy, 500Gy, 1000Gy, 5000Gy and 10000Gy respectively. The post irradiation measurements are performed at Component Division, ISAC ISRO. The measured readings are analysed and compared with the pre irradiation behaviour of the devices.

RESULT AND DISCUSSIONS

1. Shift in the threshold voltage

When the primary electrons reaches the gate oxide of a MOSFET it generates electron- hole pair. 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-SiO2 interface side and are trapped. Conversely for a negative gate voltage, holes move to the metal side and become trapped there. In absence of electric field under zero gate voltage, the holes diffuse isotropically [3]. The Subthreshold I-V characteristics of n-channel 2N6768 for various irradiation dosage is shown in Figure 1.



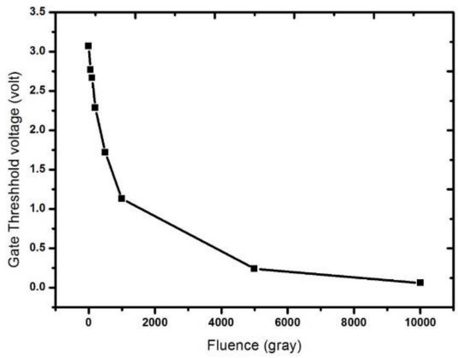


Figure 1: Output Characteristics – Plot between Drain to Figure 2: Variation of Gate Threshold Voltage Source Voltage & Drain Current for various dosagewith dosage

For n – channel power MOSFET, the threshold voltage becomes negative due to radiation induced positive charges dominated 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

$$\Delta V_{TH} = (q / C_{OX}) \Delta N_{it} \quad \text{---------------------------(1)}$$

Where q is the charge, N_{it} is the oxide silicon boundary concentration and C_{OX} is the capacitance per unit area. The threshold voltage shift component associated with radiation induced interface state 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 is represented in the Figure 2.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.

2. Increase in the Sub threshold 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. In N-channel power MOSFET 2N6768 the leakage current increases shown in the figure 3. This increase is caused by the shift in the threshold voltage and 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 dosages. It is four that the ON drain current increased with dosage.

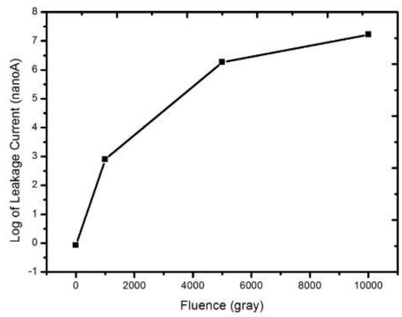


Figure 3: Variation of Leakage current with Dosage

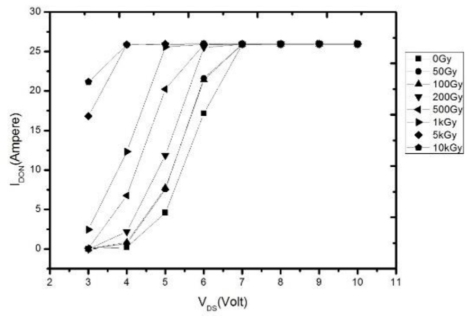


Figure 4: Transfer Characteristics – Plot between Drain to Source Voltage and ON Drain Current for various dosage.

3. Decrease of Mobility and Transconductance

The mobility degradation after irradiation is related to increase of interface traps, since the conduction of MOS transistor is due to carrier motion close to silicon oxide interface. The post-irradiation mobility can be expressed by the following empirical formula.

$$\mu = \frac{\mu_o}{1 + \propto (\Delta N_{it})} \quad \text{--------------------------------} \; (2)$$

Where μ_o is pre-irradiation mobility, ΔN_{it} is the increase of the interface traps and α is a parameter whose value depend on the technology. The degradation of the mobility will cause degradation in Transconductance which is shown in Figure 5.

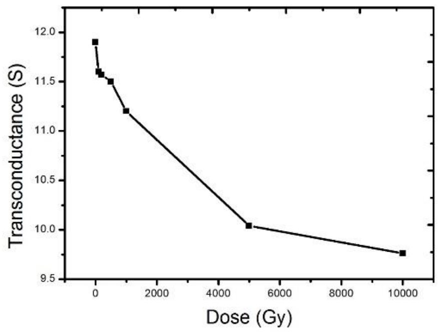


Figure 5: Variation of Transconductance of MOSFET with dosage

The transconductance (g_m) is proportional to the mobility (μ) in the linear region and with saturation current it is proportional to half the value of μ [5]. The decrease in transconductance will decrease the driving capability of the device.

CONCLUSION

The space grade power MOSFET 2N6768 when exposed to high energy electrons induces increase in the leakage current which may be critical when the transistor is used as a switch caused by the shift in threshold voltage and decrease in the gate threshold voltage. The transconductance of the device is found to decrease which may lead to lower the driving capacity of the device.

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