Threshold Voltage and Drain Current Investigation of Power MOSFET ZVN3320FTA by 2D Simulations

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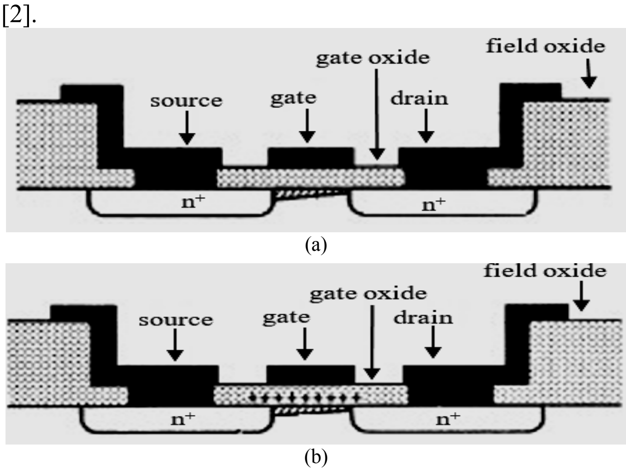
***Abstract*—Power electronic devices used in space shuttles experience degradation due to their sensitivity towards surrounding radiations. Generally, Metal-Oxide Semiconductor Field Effect Transistors (MOSFET) are used in these devices because of their fast switching speed and low power consumption capabilities. Ionizing radiation causes induced charge to build-up which damages the electrical characteristics of the MOSFET. This study investigates the threshold voltage shifts and drain current degradation for N-channel power MOSFET ZVN3320FTA by simulating experimental data on COMSOL Multiphysics. Total Ionization Dose (TID) degrade the oxide layer of MOSFETs by inducing interface-trap and oxide-trap charges. Generation of these excessive electron-hole pairs eventually causes threshold voltage shifts and current degradation.**

***Keywords*- Electrical characterization; simulation; threshold voltage shift; drain current degradation**

I. INTRODUCTION

Power electronics used in space applications are made of MOSFETs. Advanced technologies are used to make these devices more efficient and resilient to any damages caused to their electrical characteristics by TID effects. Device degradation occurs when significant charge built-up occurs after radiation strikes the sensitive oxide layer [1]. The number of fixed oxide charges start varying when more electron-hole pairs are introduced to the existing ones. Radiation hardened semiconductor devices are designed to tolerate the radioactive environment of space where several types of radiations are present and proper research is required before manufacturing them, because some radiations could reduce the device lifetime due to TID effect [2].



(b)

–Figure 1. Schematic diagram of MOSFET for (a) normal operation (b) post-irradiated operation [4]

This study has been carried out to analyze threshold voltage shifts and degradation of current by simulating experimental data. Experimentation has been validated with 3MeV of electron radiation, which is incident on commercial silicon n-channel MOSFET ZVN3320FTA with a dose level range of 0-250 KGy [3].

Fig. 1(a) illustrates a MOSFET operating normally. When gate voltage is supplied, and an inversion channel is created, and the device turns ON. Fig. 1(b) shows the effect of ionizing radiation. Due to the extra holes at the interface of oxide and substrate the threshold voltage shifts negatively, and the device remains ON even when no gate voltage supplied [4].

A. Metal-Oxide-Semiconductor Field Effect Transistor

A MOSFET is a device used for amplification and rectification of voltage and current. It works with the principle of supplying voltage at the gate terminal to create a pathway for conducting current for the purpose of amplification or switching. Ionizing Radiations around Earth's atmosphere damage these characteristics of MOSFETs and causes unwanted disturbances or even operational failures in the device. TID effects and Displacement Damage (DD) mechanisms are the most probable causes of these disturbances [5].

B. Related Work

This study has been carried out to analyze threshold voltage shifts and current degradation by simulating experimental data from experiments done on a commercial power MOSFET ZVN3320FTA. This Experimentation has been validated with the use 3MeV of electron beam radiations on this device, with a dose level range of 0-250 KGy by [3]. The simulation is done using COMSOL Multiphysics to validate the results gathered experimentally.

II. RADIATIONS AND THEIR DAMAGING MECHANISMS

Electronic circuits in space shuttles made using MOSFETS are prone to the different types of radiations present in various areas of space, hence they need to be designed accordingly to ensure they work accurately [6].

A. Origin of Space Radiation

Several kinds of radiations are present in the solar system such as protons, electrons, and neutrons [6]. They are created due to thermal movements inside the Earth's core which generates a magnetic field, known as a magnetosphere around the earth. Different particles including protons, electrons, and neutrons revolve around these magnetic field lines having different energy and strength [7]. According to [8], one source of radiation in the space are the Van Allen radiation belts, which consist of high energy protons reaching up to energies of 20-80 MeV and electrons reaching an energy level of 20-1000 keV.

B. Total Ionizing Dose Effect

TID effect occurs when electron-hole pairs are generated due to of energy transferred from the radiation beam to the electrons and holes inside the oxide layer. Fig. 2 illustrates the phenomena of electrons traveling to the gate and the holes traveling towards the oxide/substrate interface. Some of the holes gather at the SiO2-Si interface. These holes may get trapped at this interface, increasing the number of fixed oxide charges in the oxide.

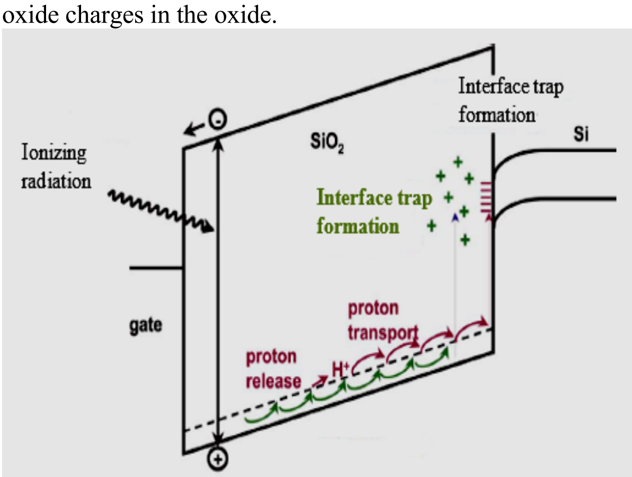


Figure 2. Schematic of TID effects caused by ionizing radiation in the oxide [9]

III. MODELLING

The equations used to evaluate the shifts in threshold voltage and drain current are acquired from [10] [11] which are used to obtain the results taken from COMSOL Multiphysics.

A. Threshold Voltage

The following model of threshold voltage is derived in [10] and it consists of the flat band voltage, surface potential, and the oxide voltage.

$$V_g = V_{FB} + \phi_f + V_{OX} \tag{1}$$

The relation of charge density and intrinsic concentration with the surface potential is shown in (2).

$$\phi_f = \left(\frac{kT}{q}\right) \ln\left(\frac{N_a}{n_i}\right) \tag{2}$$

The flat band voltage is a function of the charges between the metal and the semiconductor in the given length of oxide layer.

$$V_{FB} = \phi_{MS} - \frac{Q_f}{C_{ox}} - \frac{1}{C_{ox}} \int_0^{d_{ox}} \frac{x}{X_{ox}} \rho_{ox}(x) dx \tag{3}$$

The oxide voltage is a function of the depletion charges in the oxide layer. The capacitance of the MOSFET changes when the number of charges is changed inside the semiconductor.

$$V_{ox} = \frac{Q_d}{C_{OX}} \tag{4}$$

The capacitance of the oxide changes due to the changes in the charge density inside the oxide layer. The capacitance of the oxide is given by (5). ϵ_o and ϵ_r are the permittivity of the oxide layer and d_{OX} is the thickness of the oxide layer which is affected due to the changes in the number of charges.

$$C_{ox} = \frac{\epsilon_{ox}}{d_{ox}} = \frac{\epsilon_o . \epsilon_r}{d_{ox}} \tag{5}$$

B. Drain Current

Structure for drain current equation is acquired from [11]. The drain current is calculated by using (6) at any specific drain and gate voltage,

$$I_D = \mu C_{ox} \frac{W}{L} \left[(V_{GS} - V_T) V_{DS} \; \frac{V_{DS}^2}{2} \right] \tag{6}$$

The drain current in the initial stages of current conductance, the charge in the total inversion layer is given by (7),

$$I_D = \frac{Q_{inv} WL}{t_r} \tag{7}$$

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The drain current for a constant velocity of carriers implies a constant electric field is expressed by (8),

$$I_D = -\mu Q_{inv} \frac{W}{L} V_{DS} \tag{8}$$

Assuming the inversion charge density is constant Q_{inv} can be given by the oxide capacitance per unit area by (9).

$$Q_{inv} = -C_{ox}(V_{GS} - V_T) \tag{9}$$

The overall drain current model can be written as,

$$I_D = \mu C_{ox} \frac{W}{L} (V_{GS} - V_T) V_{DS} \tag{10}$$

The current for the semiconductor at varying drain and the gate voltages is given by (11),

$$I_D = \mu C_{ox} \frac{W}{L} \left[(V_{GS} - V_T) V_{DS} \ \frac{V^2_{DS}}{2} \right] \tag{11}$$

IV. SIMULATION DETAILS

The simulation was done using COMSOL Multiphysics by creating a 2D model of an N-channel MOSFET. The change in the threshold voltage value with varying parameter of oxide thickness is represented graphically. Fig. 3 shows the basic geometry of MOSFET which is created before the model is made. The doping concentrations of n-type and p-type particles is inserted to create the 2D model which is simulated using varying voltages.

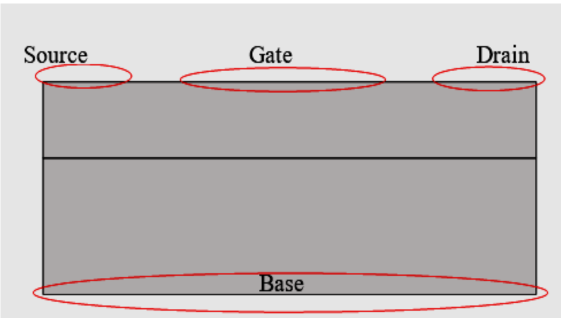


Figure 3. MOSFET geometry created in COMSOL Multiphysics

The proposed structure has been simulated in COMSOL Multiphysics software by creating a 2D model of an N-channel MOSFET. In Fig.4 (a), the schematic diagram of the geometry of a basic MOSFET is depicted where the MOSFET's Drain, Source and Gate terminals are visualized.

Fig. 4(b) shows the creation of inversion layer between source and the drain when the same gate and threshold voltage is applied to the 2D model. This inversion layer usually conducts the flow of current in a channel with full of electrons. Previous studies have shown that the drain current of n-channel MOSFET increases and the threshold voltage shifts positively [12].

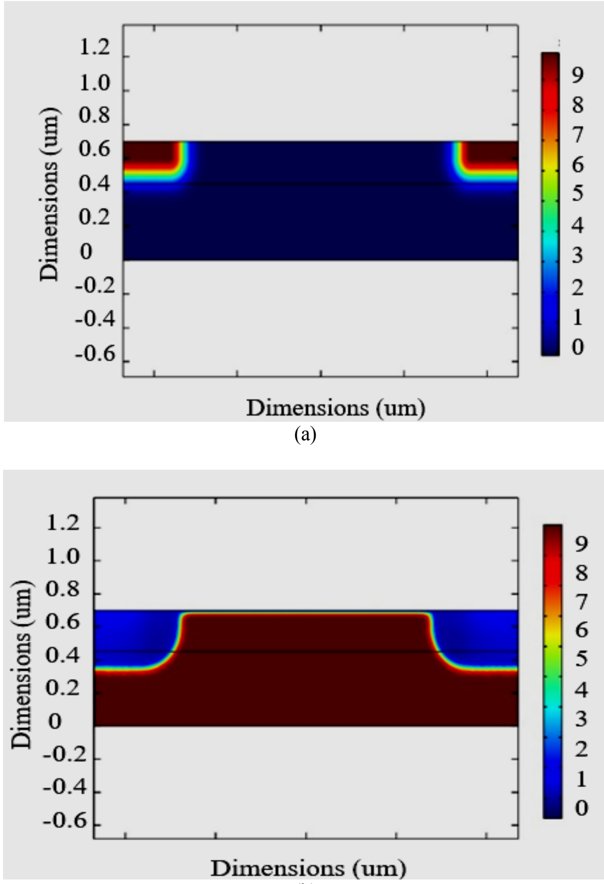


Figure 4. Schematic diagram of MOSFET (a) 2D modal for N-channel MOSFET, showing doping concentration (b) 2D modal for N-channel MOSFET, showing the inversion layer.

V. RESULTS AND DISCUSSION

The results obtained through simulating the MOSFET at various experimental dose levels, observing the changes in the oxide thicknesses and the changing threshold voltages. The results are explained using graphical representations.

A. Threshold Voltage Shift

The 2D modal of MOSFET created in COMSOL Multiphysics was used for simulation. A range of 55nm – 135nm oxide thickness was used to simulate and obtain threshold voltage values in normal functionality and post-radiated operations. Fig. 5 reveals that the suitable initial threshold voltage is nearly 2.2 V, which turns ON the device. This voltage signifies the normal operation of the device. The oxide thickness at this stage is 55nm and the capacitance of the oxide layer given by (5) is 7.24x10-8 F/cm2. According to equation (5), due to its inverse relationship, the capacitance of the oxide decreases when the thickness of oxide increases.

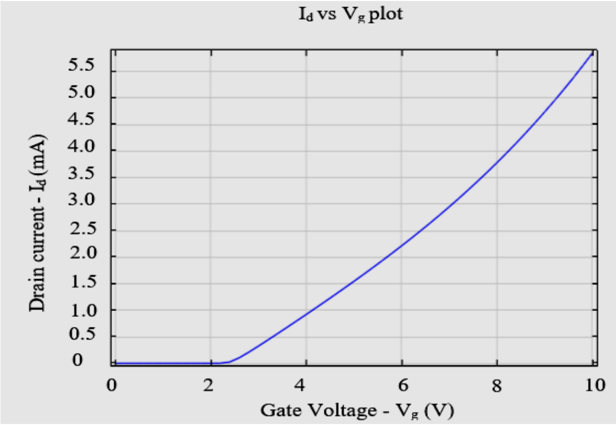


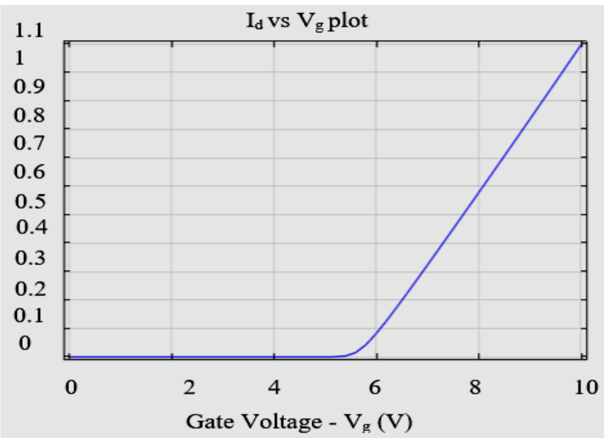
Figure 5. MOSFET geometry created in COMSOL Multiphysics

Table I summarizes the changes in the threshold voltage required to turn ON the MOSFET with respect to the changes occurred in the oxide thickness.

TABLE.I. THRESHOLD VOLTAGE BEFORE AND AFTER THE OCCURRENCE OF A SHIFT

No	Oxide Thickness (nm)	Threshold voltage (V)	Threshold voltage (V) (normal operation)	Threshold voltage shift (V)	Experimental dose level (KGy) [3]
1	90	5.2	2.2	3.0	50
2	105	5.6	2.2	3.4	100
3	120	6	2.2	3.8	150
4	135	6.6	2.2	4.4	200

Eventually, a greater number of electrons are required to turn ON the device again. In this case, the n-channel MOSFET has a positive threshold voltage shift, which means more positive voltage is applied to turn ON the device. Hence, a higher gate voltage is obtained when oxide thickness changes to 135nm.



(a)

Figure 6. (a) post-irradiation threshold voltage identification at oxide thickness of 90nm

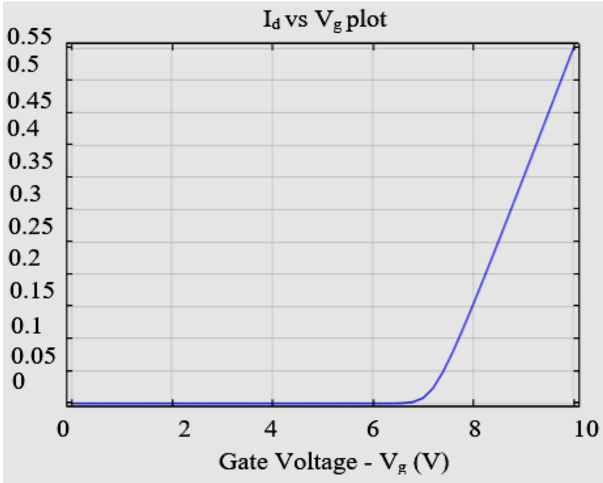


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Figure 6. (b) post-irradiation threshold voltage identification at oxide thickness of 135nm

Fig. 7 shows the overall results of threshold voltage shift vs. oxide thickness. The range of oxide thickness change is 90-135nm for post-irradiated simulation and the threshold voltage shift is recorded to be in the range of 3-4.4V. The threshold voltage values ranged between 5.2V-6.6V.

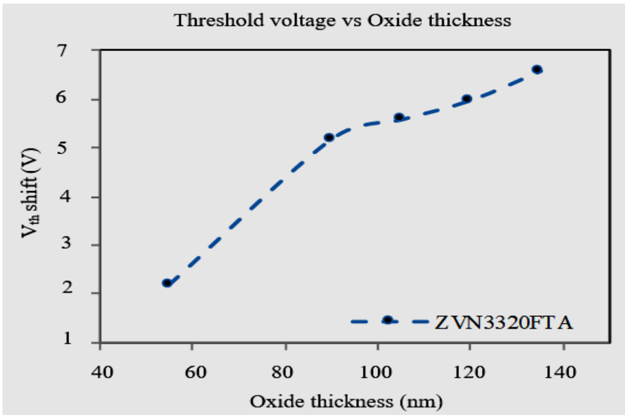


Figure 7. Overall threshold voltage shift vs. oxide thickness.

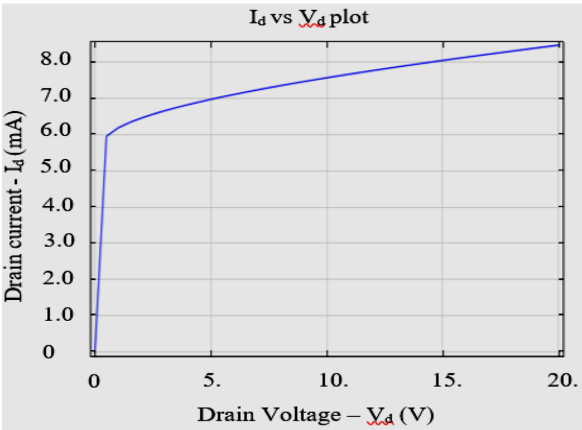
B. Current Degradation

When the threshold voltage of a MOSFET shifts because of radiation, its drain current is also degraded as the main reason for these defects are the changing number of charges in the oxide layer. Electrons generated due to radiation move towards the interface traps where these traps behave like scattering center for electrons. There is a possibility that the defects created due to the generation of electron-hole pair might trap more electrons when a gate voltage is applied. This phenomenon increases the threshold voltage [13]. Fig. 8(a) shows the drain current in the normal condition of the device before it is exposed to any radiation at an oxide thickness of 55nm. The current value when 10V is applied at the drain is 7.5mA. Fig. 8(b) shows the effects of radiation on the device when the oxide thickness becomes 135nm and the value of the current increases to 470mA at an applied drain voltage of 10V. The major cause of increase in drain current is the increase in number of oxide charges. This happens when high kinetic energy from these radiations is transferred to the static fixed charges in the oxide. When these static charges gain energy, they become ionized and contribute to the number of electrons and holes present in the oxide layer, eventually increasing the total number of charges.

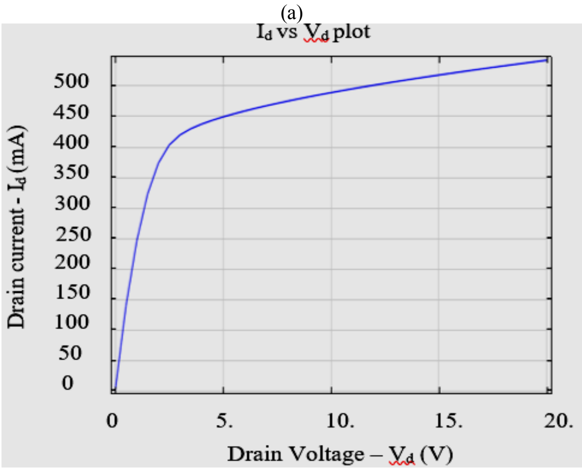
TABLE II. DRAIN CURRENT DEGRADATION

No	Oxide Thickness (nm)	Threshold Voltage (V)	Drain Current (mA)
1	55	2.2	7.6
2	90	5.2	56
3	105	5.6	152
4	120	6	294
5	135	6.6	490

Table II summarizes the effects of threshold voltage shift caused on the drain current given by (11), calculated using the threshold voltage values at the specific oxide thickness.



(a)



(b)

Figure 8. (a) Drain current at oxide thickness of 55nm before radiation exposure (b) Post-irradiation drain current at oxide thickness of 135nm

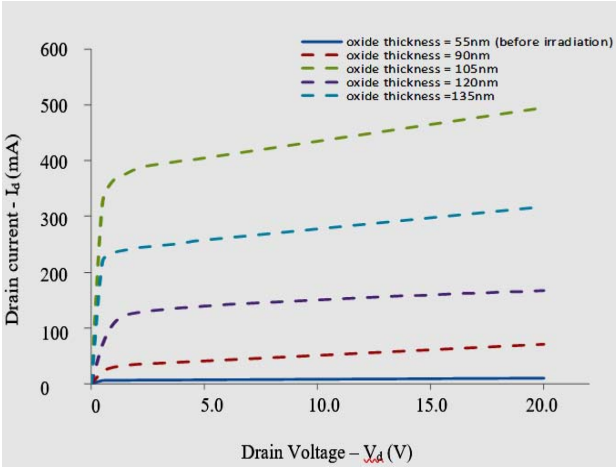


Figure 9. Summary of drain current degradation

Fig.10 shows the graphical results of the drain current. The trend clearly shows the increase in the magnitude of the current.Fig. 9 shows the summary of the effect of the range of oxide thicknesses used to simulate the variations in drain current by applying a drain voltage of 0-20V. During normal and un-irradiated condition of the device, the current at the output is around 7.6mA and the maximum variation in drain current can be seen when the oxide thickness is at 135nm.

C. Simulation Vs. Experimental Results

The Comparison between the experimental and simulated values are tabulated in table III The error percentage between the experimented and simulated values of the threshold voltage is 4.8% and for drain current, it is 14.6% as shown.

TABLE III. COMPARISON BETWEEN EXPERIMENTAL AND SIMULATED VALUES

No	Parameters	Experiment (0-200KGy)	Simulation (55-135nm)	Percentage Error (%)
1	Gate-source voltage (V)	2.2-6.6	2.2-6.3	4.8
2	Drain current (mA)	11.5-410	7.5-470	14.6

VI. CONCLUSION

The results from the Simulation show that the threshold voltage shifts positively for an N-channel MOSFET and its current degradation is also positive. The main reason for these phenomena is analyzed and the flaws induced after the MOSFET is irradiated. The theory of generation and recombination of electron-hole pairs are the main mechanism that results because of TID effect, causing charge imbalance in the semiconductor. Moreover, from the study, the N-channel MOSFETs, interface traps are the reason for positive shifts in the threshold voltage and oxide traps are the reason for negative shift threshold voltage. Finally, the analysis of an n-channel MOSFET is accomplished with simulation and comparisons are taken up with the conventional results. It is clearly observed from the comparison that the defects created by radiations changes the physical state of the device, which degrades and ultimately causes device failure.

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