Chapter IV

Response of MOSFET under Bias Condition to the Radiation at Room Temperature (On Line Measurements)

The response of MOSFET under bias condition for different kinds of radiations has been studied. The investigation reports on the irradiation of gate bias MOSFET at \( V_g = \pm 1.5 \text{V} \), which is higher and lower than the threshold voltage (i.e. \( V_{th} = -1.1 \text{V} \)) and gate voltage just near the threshold voltage i.e. \( V_g = -0.9 \text{V} \) using 6MeV energy electrons, Co-60 Gamma Rays, bremsstrahlung radiation, 100MeV energy Ag, Ni and I ions respectively. The basic hoping electron transport mechanism in silicon dioxide and details of variation in energy level diagrams of MOS structure are given. The pre and post irradiation characteristics have been measured using electrical techniques such as I-V, subthreshold current, C-V and G-V measurement. Also, the details of radiation sensitive parameters under biased condition are discussed. The results show that the parameters of the MOS device under bias and irradiation condition shifts in large amounts as compared to the unbiased condition. The shift in \( V_{th} \) found to be around -0.18V at zero gate bias, but in case of \( V_g = +1.5 \text{V} \) for 6MeV energy electron irradiation shows small negative shift of \( V_{th} \) as compared to the bias at \( V_g = -1.5 \text{V} \). Such results are mainly attributed to the MOS device irradiated under positive bias found excess negative field induced in the channel and this field acts as a barrier for carrier electrons to recombine with the radiation induced states at the interface. Hence, it shows more negative shift in the threshold voltage under bias condition. In case of swift heavy ions, MOSFET under bias condition shows \( V_{th} \) shift towards smaller negative direction for lower ion fluence and higher positive direction for higher fluence i.e. recovers to its initial value called rebound effect. Overall, results show that TID (Total Induced Dose) mechanism depends on irradiation of device under biased conditions due to different carrier transport mechanism and contribution of oxide and interface states.
4.1 Introduction

The charge carriers in the region beneath the gate oxide between source and drain in MOS-device develops specific region i.e. called as channel. The behavior of these carrier depends upon the applied transfer and longitudinal field to the gate and drain electrodes. These fields are affected temporarily or permanently by interaction of energetic radiation, due to high sensitivity of MOS-devices. The most important fundamental parameters of MOS-device are transconductance ($g_m$), threshold voltage ($V_{TH}$), mobility ($\mu$) of charge carriers. These parameters are responsible for switching characteristics and the overall response of the device depends on the field developed in the dielectric region of MOS-device under irradiation. It causes failure of main functioning of device by exposure to radiation in space and other radiation environments. [1-3] Therefore, these parameters especially in weak inversion have been of considerable interest for many years, because the behavior of such parameter must be accurately known for device design and circuit simulation process in the development of radiation hardened electronic devices.

As spacecraft designers use increasing numbers of commercial and emerging technology devices to meet stringent performance, economic and schedule requirements. The ground-based testing of such devices for susceptibility to different irradiation effects has assumed ever greater importance. Recent experience in satellite design has also emphasized the increased susceptibility of biased unipolar and bipolar devices to damage from total ionizing dose (TID). Because, the payload of spacecraft and in every radiation environment all electronic devices have been mostly under biased mode.

The energetic radiation induce charges, which exists mainly at or near the interface and oxide region, shows large variation in parameters depends on the biasing condition at the time of irradiation. Some of these trapped charges correspond to positively charged buildup by holes in the oxide and results into the developing of positive surface potential at the Si-$SiO_2$ interface. As well as some of the holes slowly transported in oxide and encroaches towards the interface by interacting with interface bonding results into break them to produce dangling bonds. The charge carriers in channel experiences a Coulombic force, tunneling effects, scattering phenomena with interface, such effects on carriers depend on applied bias condition at the time of irradiation. This is continuing controversial problems in overall operation of MOS-devices.
4.2 Irradiation Effects of MOSFET’s under bias condition

4.2.1 Mechanism

Operation of MOS transistor can be achieved by applying lower sufficient biasing voltage at drain and gate terminals. In case of inversion region of MOS-transistor a positive voltage is applied to the gate electrode, which repelled positive charge far enough from the surface of the oxide capacitance to allow n-channel to form. The concentration of charge carriers in channel depends on the amount of voltage applied to the gate electrode, which allows current to flow from source to drain. More specifically, applied voltage to the gate electrode must be above threshold voltage. When energetic radiation interacts with MOS structure (inversion mode) as shown in Figure 4.1, the probability to separate out the developed e-h pairs in the oxide is more due to large potential difference. It increases the mobility of hole hopping transport process and at the same time recombination probability decreases. It results into the increase in density of induced interface states and oxide states at the interface and bulk oxide region respectively and influence the large band bending of energy levels at the interface [1].

In depletion region, the intermediate state occurs when a large negative voltage is applied to the gate electrode. This causes positive charge to accumulate on the top of the oxide layer. This positive charge on the top plate of an imaginary capacitor attracts negative charge to the bottom plate. However, since the voltage applied is not enough to
completely disburse the entire negative charge in the channel of the device, therefore inbuilt space charge region develop below the gate oxide at the Si-SiO$_2$ interface called as depletion region. Within a depletion region, the presence of mobile carriers is zero which causes no current to flow in between source to drain. Specifically, applied voltage to the gate electrode is less than its characteristic threshold voltage. When energetic radiation interacts with depletion region of the MOSFETs as shown in Figure 4.2, the probability to separate out the developed e-h pairs in oxide is more due to large potential difference in the oxide. It increases the mobility of hole hopping transport process towards negative gate electrode and at the same time recombination probability decreases. Therefore, it results into the decrease in the density of induced interface states and increase fixed oxide trapped charges in gate oxide region. These charges are mainly responsible to bend the energy levels from down to top [2-3].

Figure 4.2: Schematic of variation in energy band of irradiated MOS-structure under biased condition (Depletion mode).

The response of channel carrier density fluctuation at the time of operation of MOS-device in weak inversion region is due to localized charges either fixed oxide charges or interface state charges. The carrier fluctuation and columbic scattering are comparatively less at lower drain ($V_{DS}$) and gate voltage ($V_G$), i.e. just above the
threshold voltage ($V_{th}$) of MOS-device. As well as these localized charges varies due to interaction of ionizing radiation and affects directly on the mobility of charge carriers in the device [4]. Because at low electric field, the drift velocity ($V_d$) of charge carriers is directly proportional to the electric field strength $\xi$, the proportionality constant is defined as the mobility ($\mu$) in cm$^2$/V-Sec.

$$V_d \propto E \quad \text{and} \quad V_d = \mu E \quad \text{(4.1)}$$

When an electric field is applied to a semiconductor, carriers (e$^-$ and holes) are accelerated and also scattered by lattice vibration and impurity collision. The drift velocity of e$^-$ and hole in Si is depends on electric field. The mobility of electron is greater than holes; therefore there is more drain current in an n-channel MOSFET as compared to p-channel MOSFET. The carrier mobility in the bulk Si is a function of impurity doping concentration. Whereas, in the MOSFET, mobility of charges is not depend only on impurity concentration, but they also depend on interface surface-roughness, number of interface states, localize columbic field etc., as shown in Figure 4.3. In this case channel mobility, $\mu_{ch}$ is mainly a function of the effective electric field normal to the Si-surface [5].

$$\mu_{ch} = \mu_0 \left( \frac{E_{crit}}{E_{eff}} \right) \quad \text{(4.2)}$$

Where, $\mu_0$ - mobility at critical electric field, $E_{crit}$ - Critical field and $E_{eff}$ - Effective electric field.

![Figure 4.3: Schematic representation of scattering sources responsible to move channel carrier.](image-url)
4.2.2 Parameters affected under biased conditions

The different types of mobilities are given below, which are responsible to the different types of scattering sources generated by radiation under bias condition [5, 6].

i) Effective Mobility ($\mu_{\text{eff}}$)

The effective mobility is relevant with effective transverse electric field from long-channel device measurements and is assumed to be constant along the channel for constant drain voltage. It is determined from the drain conductance measured at low drain voltage. The effective mobility is a function of temperature and gate voltage. As the temperature decreases mobility increases and gate voltage increases, the carrier mobility decreases even further. It solved for mobility (known as the effective mobility $\mu_{\text{eff}}$) and is given by, [5]

$$\mu_{\text{eff}} = \frac{L_g d}{ZC_{\text{OX}} (V_{GS} - V_T - V_{DS})}$$

Usually for $V_{DS} << (V_{GS} - V_{TH})$ the equation (4.3) becomes,

$$\mu_{\text{eff}} = \frac{L_g d}{ZC_{\text{OX}} (V_{GS} - V_T)}$$

The general expression of effective mobility is frequently given by,

$$\frac{1}{\mu_{\text{eff}}} = \frac{1}{\mu_o} + \frac{1}{\mu_s} + \frac{1}{\mu_{\text{ph}}}$$

Where $\mu_o$ - Low Field Mobility; $\mu_s$ - Surface mobility and $\mu_{\text{eff}}$ - Effective mobility, $\mu_{\text{ph}}$ – Phonon scattering mobility

Another technique of effective mobility measurement for depletion-mode devices in accumulation region is the drain conductance method. In this case the device is operated in the linear region (i.e. $V_{DS} \sim 5$ to $50$ mV). When applied gate voltage in device equal to the Flat Band Voltage ($V_{FB}$), the corresponding drain current is only through bulk denoted by $I_{DO}$. If applied potential is more than $V_{FB}$, the current induced at the surface. This additional current is due to the conduction of the accumulation layer mobile electrons near the surface for given voltage. The current difference between these two potential levels is called as accumulation current ($I_{\text{accum}}$) i.e.

$$I_{\text{accum}} = I_B (V_{GS}) - I_{DO} (V_{GS} = V_{FB})$$

$$\mu_{\text{eff}} = \frac{I_{\text{cum}}}{L/W} \times \left( \frac{1}{Q_s V_{DS}} \right)$$
Where $W$ & $L$ are channel width and length of MOS device.

$Q_S$ - Total charges induced in channel.

$V_{FB}$ - Flat band voltage, which is determined from High-Frequency C-V Measurement.

The actual relation between $V_{GS}$ and $Q_S$ is as follows,

$$V_{GS} = V_{FB} + \psi_S + \frac{Q}{C_o}$$

Where $C_o$ is gate oxide capacitance, $\mu_s$ is surface potential.

The depletion-mode devices are having additional advantage that its profiles can be obtained by varying the gate voltage [6, 7].

ii) Field Effect Mobility ($\mu_{FE}$)

The field effect mobility is determined from the transconductance, $g_m$ the equation 3.8 can be written for condition $V_{DS} = V_{GS} - V_{TH}$ as below;

$$g_m = \frac{\partial I_{d(sat)}}{\partial V_{GS}} = \frac{W\mu_c C_{ox}}{L} V_{DS}$$

When this expression is solved for the mobility, it is known as the field effect mobility $\mu_{FE}$ and given by,

$$\mu_{FE} = \frac{Lg_m}{ZC_{ox}V_{DS}}$$

It shows that expression determine value of $\mu_{FE}$ without measurement of threshold voltage. In MOSFET channel carrier mobility is derived from $\sqrt{I_d - V_{GS}}$ characteristic of device in the saturation region [7].

iii) Surface Scattering mobility ($\mu_n$)

The surface-scattering mobility of channel carriers related to 1) the interaction of carrier charges to the interfering surface (i.e. to the Si-SiO$_2$ interface) 2) Coulomb scattering and 3) phonon scattering. First is most important under strong inversion condition and governed by the distance of carriers from the surface (i.e. closer the carriers to the surface interface stronger the scattering). The second coulomb scattering is important under resultant surface electric field, which is responsible due to the charge centers developed in oxide and interface region in low field region. In weak inversion (subthreshold) region, mobility variation accounts to the minority carrier density, interface states, fixed oxide charges and localized charge density or substrate doping concentrations imply increased coulomb scattering. It is less effective in strong inversion.
region due to carrier screening irrespective to the other parameters formulated using dc-conductance.

\[
\frac{g_{m}^2}{I_{d(sat)}} = \frac{2W\mu_n C_{ox}}{L}
\]

From equation 4.12 the carrier mobility can be written as;

\[
\mu_n = \frac{C_{m}}{I_{d(Sat)}} \times \frac{L}{ZWC_{OX}}
\]

Where \( C_m \) is the slope of a plot of \( (I_{DS(Sat)})^{1/2} \) against \( V_{GS} \), equation 3.13 gives carrier mobility in saturation region.

### 4.3 Experimental and Irradiation Details

The devices used for Total Induced Dose (TID) irradiation effects under bias condition were having the same configurations as per unbiased condition. In this case MOS devices were irradiated under different bias voltages at room temperature. The measurements were conducted for the MOSFETs irradiation at fixed gate and drain voltage by passing constant drain current. The radiation mainly consists of 6MeV energy electrons, Co-60 Gamma, Bremsstrahlung and swift Heavy Ions for the irradiation purpose. The responses of these devices to different radiations under biased condition were characterized using \( I_{D-V_{DS}} \), subthreshold, C-V and G-V measurement respectively. The threshold voltages, \( V_T \) for each of the MOS device were obtained separately. In case of I-V measurements the keithley make picomometer was used to measure subthreshold current, while in case of C-V and G-V measurements the MOS devices were characterized using microcomputer-controlled Lab-Equip make system, which was used to measure capacitance and conductance simultaneously at fixed frequency of 1MHz as a function of bias gate voltage.

The irradiation experiment of MOSFETs were carried out exclusively for different under bias conditions, i.e. the voltage applied just more than that of threshold level \((V_g \approx -1.1V)\), \( V_g = \pm 1.5V \) and \( V_g = \pm 7V \) respectively for constant drain to source voltage of \( V_{DS} = 10mV \). The first condition i.e. lower gate voltage helps to produce uniform distribution of surface field across the gate insulator region and to avoid hot-electron effect, whereas second condition of higher gate voltage helps to study the biased dependent radiation induced oxide and interface states. Such conditions were kept for the entire radiation damage in terms of TID.
a) **6MeV electron irradiation**

MOSFET’s under bias conditions were exposed to 6MeV energy electrons for different fluences. For this purpose, 6MeV energy electrons were obtained from the Race Track Microtron of the Department of Physics, University of Pune. The device which was mounted on the Faraday cup was given a bias voltage through a long cable and arranged the respective Faraday cup in the path of the electron beam at fixed distance in air from the extraction port of the Race Track Microtron. The schematic of the irradiation set up and online measurement circuit is shown in Figure 4.4.

![Figure 4.4: Schematic of the irradiation setup and online measurement circuit of MOSFET’s under bias condition. (No to the scale)](image)

The 6MeV electron beam was made to fall on the MOSFET under bias condition and respective electron fluence was measured using current integrator. The beam was turned off after giving a certain value of fluence to the MOSFET, which was in the range from $9 \times 10^{11} \text{e}/\text{cm}^2$ to $1 \times 10^{14} \text{e}/\text{cm}^2$. Pre and post MOSFET irradiated characterizations were performed for the prescribed value of electron fluence. Further, the same experiment was repeated for higher electron fluence.
a) Co-60 Gamma and Bremsstrahlung irradiation

MOSFET’s under bias condition were exposed to gamma and bremsstrahlung radiation for different doses. For this purpose, a Co-60 gamma source from the Department of Chemistry, University of Pune was used, whereas 15MeV linear Accelerator (LINAC) from SAMEER, Mumbai was used as a bremsstrahlung radiation source. In case of gamma irradiation, the MOS device under bias condition was kept in the Co-60 source chamber at a fixed position. While in case of bremsstrahlung irradiation, the MOS-device under bias was mounted in the path of the photon beam and the respective dose was measured in the control panel room through long cable. In both the cases the dose was varied from 10Gy to 138Gy. Pre and post irradiated MOSFETs characterization were performed for prescribed dose of gamma and bremsstrahlung radiation. Further experiment was repeated for another set of MOSFET and dose.

b) Heavy ion irradiation

The high-energy heavy ion irradiation was carried out at the 15 UD Pelletron of IUAC, New Delhi, India. For high energy heavy ion irradiation, a rectangular ladder (rod) made up of copper was used for mounting the MOSFET devices under bias condition using socket to pass the drain current in the device. Three devices could be mounted on each side with a spacing of about 5mm between two adjacent device. Device mounted on one of the sides, labeled as ‘A’. Similarly, devices were also mounted on the other remaining three sides denoted as sides ‘B’, ‘C’ and ‘D’ respectively for identification. The electrical contact between the probe of device and the ladder was made using conducting silver paste. Later on, this rod was fixed to the electromechanical system attached to the top flange of the irradiation chamber, which was connected to the material Science beam line of the Pelletron. A CCA camera was used to adjust the sample position with reference to the beam slit and the electron suppressor. The irradiation was carried out after attaining a base pressure of ~5×10^-6 mbar in the chamber. Initially, 100MeV Iodine ion beam was focused on the sample and the beam was scanned over the sample of area ~0.5cm² using the magnetic scanning facility. The ion fluence received by the device was measured by current integrator (EG & G ORTEC make, model 439) coupled to a digital counter (EG & G ORTEC make, model 832) connected by ladder. An electron suppressor was used and fixed at a distance of 5cm from the ladder on which MOS devices were mounted. Negative D. C. voltage ~1KV was applied to the suppressor. For this purpose, EG & G ORTEC make, model 480 high voltage unit was used. The number of ions falling on the sample was estimated
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from the charge state and the total charge measured in a given time period. After irradiation of devices to the desired fluence, the ion beam was turned off and new device mounted on the ladder was brought in the beam line and irradiated. In this manner all the devices were exposed to iodine and nickel ions, the details of irradiation are given in the following Table 4.1:

After ion irradiation, the ladder was taken out from the chamber and the mounted sockets biased with devices were removed from the ladder. These devices were labeled accordingly and stored into a dry atmosphere. By following the same course of action, other MOSFET devices were irradiated with 100MeV nickel and silver ions with different fluences. All the MOSFET devices irradiated with ions was in the same range of fluence.

Table 4.1: Details of the ion species, energies, fluences, electronic energy loss (Se), nuclear energy loss (Sn) and projected range in MOSFET-device used for irradiation

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Ion</th>
<th>Ion Energy (MeV)</th>
<th>Ion Fluence (ions/cm²)</th>
<th>S_e, (eV/Å)</th>
<th>S_n, (eV/Å)</th>
<th>Project Range (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Iodine (I)</td>
<td>100</td>
<td>1×10^9, 5×10^9, 1×10^10</td>
<td>1053</td>
<td>8.502</td>
<td>16.23</td>
</tr>
<tr>
<td>2</td>
<td>Nickel (Ni)</td>
<td>100</td>
<td>1×10^9, 5×10^9, 1×10^10</td>
<td>719.8</td>
<td>1.357</td>
<td>20.17</td>
</tr>
<tr>
<td>3</td>
<td>Silver (Ag)</td>
<td>100</td>
<td>1×10^9, 5×10^9, 1×10^10</td>
<td>1051</td>
<td>5.931</td>
<td>15.71</td>
</tr>
</tbody>
</table>

4.3 Results and Discussion

The energetic radiation loses its energy in the semiconductor medium through ionization and excitation, which contributes in terms of the radiative and collisional energy loss. Because the radiation energy is sufficiently high to generate displacements damages within the lattice, by knocking out the silicon atoms which is, termed as collisional energy loss [8]. It induces electron-hole pairs in the bulk material by Si-O bond breaking events as well as at the Si-SiO₂ interface. The positive charge trapped in the oxide, N_OT is contributed by those oxygen bonds, which are broken due to the electron-hole trapping events in the SiO₂ dielectric [9]. These bond-breaking events also contribute to the formation of interface states, N_IT by buildup of negative charge at the dangling bonds formed at Si-SiO₂ interface [10]. But under bias condition, irradiation seems to lead qualitatively different oxide and interface traps charge buildup and shows different effects on general annealing behavior of the MOS device.
4.3.1 6 MeV energy electrons

The variation of drain current, \( I_d \) with drain to source voltage, \( V_{ds} \) measurement for two different gate bias viz \( V_g = +1.5 \) and \(-1.5 \) respectively for 6MeV electron irradiation is shown in Figures 4.5. It is observed from figure that in case of under bias irradiation at fluence \( \phi = 1.5 \times 10^{13} \text{e}/\text{cm}^2 \) and gate bias value, i.e. \( V_g = -1.5 \), the saturation current and pinch off voltage found to be increased as compared to pre irradiation condition. But, at the same electron fluence for bias at \( V_g = +1.5 \), the saturation current and pinch off voltage found to be decreased and same trend observed for the bias at \( V_g = +7 \). This is the evidence of generation of negative interface states, \( \Delta N_{IT} \) increase rapidly with electron fluence and later on saturates at higher electron fluence around \( \phi = 8 \times 10^{11} \text{e}/\text{cm}^2 \) for positive or zero gate bias. While in the case of a negatively biased of the MOS device, the results found to be reverse, i.e. the number of negative interface states, \( \Delta N_{IT} \) initially decreases with increasing electron fluence and shows a turnaround effects at the fluence of \( \phi = 150 \times 10^{11} \text{e}/\text{cm}^2 \). At the same time, it is also observed that the positive oxide states, \( \Delta N_{OT} \) increases rapidly with increasing the electron fluence. But these states are not influenced by the gate bias because it is observed that radiation induced positive oxide states, \( \Delta N_{OT} \) are almost the same for all the applied gate bias. This means that the oxide charge trapping (i.e. trapping of hole) in the SiO\(_2\) is independent of the bias, which may be associated to the low hole mobility and deep traps in the SiO\(_2\) layer. But in the case of, \( V_G = -1.5 \), the radiation induced negative interface states, \( \Delta N_{IT} \) measured to be less at the Si-SiO\(_2\) interface. It is due to generated interface states were filled with excess electrons tunneling from the substrate, so as there is less number of free states to be occupied and large positive oxide trap charges generated at the time of irradiation. As a result the saturation current and pinch off voltage observed to be increased in negative bias and decreased in the positive bias.

The variation in \((I_d)^{1/2}\) with gate to source voltage, \( V_g \) measured for 6MeV energy electron irradiation at the fixed fluence of \( \phi = 1.2 \times 10^{12} \text{e}/\text{cm}^2 \) under bias at \( V_G = +1.5 \) and \(-1.5 \) respectively shown in Figures 4.6. From figure it is observed that in all the cases for under bias condition the saturation drain current almost remain constant. Result also shows that at negative gate bias of \( V_g = -1.5 \), a marginal negative shift observed as compared to positive gate bias of \( V_G = +1.5 \). From this result it is also observed that at \( V_G = -1.5 \) the threshold voltage, \( V_{th} \) increases in the negative direction from -1.88V to -2.23V and corresponding transconductance, \( g_m \) found to be decreased from 204\(\mu\)mho to
156 µmho respectively. Whereas in case of positive gate bias of \( V_G =+1.5\text{V} \), the threshold voltage, \( V_{th} \) increases in the negative direction from -1.88V to -2.93V and found to be substantial decreased in transconductance from 204µmho to 48.25µmho as compared to the negative gate bias. This is mainly attributes to the radiation induced negative interface states, \( \Delta N_{IT} \) and positive oxide states, \( \Delta N_{OT} \) are directly related to the total energy deposited by the 6MeV energy electron in the MOS structure.

This energy is being deposited in the dielectric medium mostly through collisional process i.e. \(~1.65\) MeV-cm\(^2\)/g and radiative process i.e. \(~1.37\times10^{-1}\) MeV-cm\(^2\)/g [10]. It is understand that the energetic electrons pass through the MOS structure having thickness 350µm and assumed that the energy deposits almost uniformly within the SiO\(_2\) dielectric and at the Si-SiO\(_2\) interface.
As the energetic electrons pass through the Si-SiO₂ interface, the Si-SiO₂ bond breaking events take place due to the large collisional energy, thus creating empty states at the interface. If an electron is associated with such a state during the device operation generates the negative field at the interface, thus enhancing the drain conductance, $g_d$. When the devices irradiated under positive bias, its excess negative field induced in the channel, thus acts as a barrier for electrons to recombine with the radiation induced states at the interface hence shows the more negative shift in the threshold voltage. These results have also been confirmed using C-V technique. The variation in capacitance (C) with gate voltage ($V_g$) at different 6MeV energy electron fluences for the various bias conditions of n-MOSFET is shown in Figure 4.7. From figure it is observed that in case of $V_g$=-1.5V bias condition, the C-V curve shifts toward higher negative gate voltage, whereas, at $V_g$=+1.5V bias condition, the C-V curve observed to be shifted towards higher positive gate voltage. This result may attributes to the generation of radiation induced interface states which mainly depends on the respective positive and negative bias greater than that of oxide states. Moreover, the result also shows that the interface states are assign to positive charge when it is under negative bias. Whereas, assign negative charge when it is under positive bias during irradiation. The radiation generated interface states are activated and show more response in case of conductance measurement. The variation in conductance ($G_m$) with gate voltage ($V_g$) at different 6MeV energy electron fluences for the various bias conditions of n-channel depletion MOSFET is shown in Figure 4.8. From figure it is observed that MOSFET under positive (i.e. +1.5V, +7V) and negative (i.e. -1.5V, -7V) gate bias buildup the space charge in the
SiO₂ and Si- SiO₂ interface, which shows an appropriate shift in \(G_m-V_g\) curve. The negative bias of G-V curve shifts toward the more negative direction as compared to the positive bias condition. This attributes to the introduction of more positive space charge in to the oxide or at interface. This is most probable due to predominant trapping of holes in the oxide under negative bias condition. From these results, it is also infer that the oxide charge is not directly associated to electron trapping during irradiation. Whereas, in case of positive bias, the probability of generation of neutral defects in the oxide region increases due to the annealing of traps through the injection of the electron from the channel into the oxide, which does not show any positive shift in \(G_m-V_g\) curve.

The contribution of irradiation-induced negative trapped charges, \(\Delta N_{IT}\) at the SiO₂–Si interface and positive trapped charges \(\Delta N_{OT}\) in SiO₂ towards threshold shift \(\Delta V_T\) as a function of 6MeV electron fluence at gate bias voltage of \(V_g = +1.5V\) and -1.5V respectively is shown in Figure 4.9. The marginal change in the positive oxide states, \(N_{OT}\) can be associated to the thin and good quality of SiO₂ gate. The saturation at high fluence is natural due to the "annealing" effect of the incident electron fluence [12]. The entire set of 6MeV electron beam irradiated MOS devices exhibit degradation in the threshold voltage, \(V_T\). The negative shift in threshold voltage, \(V_T\), corresponds to an increase in the negative interface states, \(\Delta N_{IT}\) and increase in positive oxide charge, \(\Delta N_{OT}\). But, in this case the increase in the threshold voltage, \(V_T\) can only be associated to the radiation induced interface states, \(\Delta N_{IT}\). But, a good SiO₂ gate can be an advantage for smaller positive charge traps as, \(\Delta N_{OT}\). While, the screening of free and acceptor states by
selective bias (here, negative bias) can thus reduce the total charge content during formation of irradiation-induced charge states. Hence in the low fluence regime, i.e. electron fluence is less than around \( \phi \sim 8 \times 10^{11} \text{e/cm}^2 \) the bond breaking events and the charge compensation by tunneling from the substrate compete each other. But as the electron fluence increases thereafter the damage creation mechanism is much more dominant, which is later on, suppressed by the damage annealing process.

Figure 4.9: Variation in net threshold shift, \( \Delta V_T \) and contribution to \( \Delta V_T \) due to interface states, \( \Delta V_{NI} \) and oxide states, \( \Delta V_{NOx} \) with different 6MeV electron fluences at fixed value of \( V_{DS} = 0.2 \text{V} \) for n-channel depletion MOSFET’s under bias \( V_g = \pm 1.5 \text{Volt} \).

This process can only be over ridden by the choice of bias during irradiation. Obviously this effect is observable only for \textbf{low biases during irradiation}, which is responsible for the partial filling up of the trapping sites. In case of large bias, completely filled or completely empty states will not affect the trapping capacity. Obviously, this effect is observable only for bias voltages during irradiation, which is responsible for the partial filling up of the trapping sites. Because in the case of large bias voltages, due to band bending, completely filled or completely empty states will not affect the trapping capacity. The variation in drain current (\( I_{DS} \)) with drain to source voltage (\( V_{DS} \)) at different 6MeV energy electron fluences for fixed value of \( V_{gs} = -0.9 \text{V} \) of n-channel depletion MOSFET’s under bias condition is shown in Figures 4.10. In such low gate biasing condition i.e. just above the threshold voltage of device (i.e. \( V_{th} = -1.1 \text{Volt} \)) and small positive drain voltage i.e. \( V_{DS} = 10 \text{mV} \) during irradiation helps to achieve uniform
channel and in addition electric field distribution along the channel also helps to reduce the minority carrier fluctuation in the channel. From figure it is observed that $I_d$ seem to be very small at pre-irradiation condition and saturates drastically even at the small value of $V_{DS}=100\text{mV}$. But, after irradiation with 6MeV energy electrons, the $I_{ds}$ saturation, pinch off voltage and drain conductance ($g_d$) found to be increased substantially with increase in the fluence from $25 \times 10^{11} \text{e/cm}^2$ to $12 \times 10^{13} \text{e/cm}^2$. The variation in drain conductance ($g_d$) with different 6MeV energy electron fluences for n-channel depletion MOSFET's under biased at $V_{GS}=-0.9\text{V}$ is shown in Figure 4.11. From the figure it is observed that initially $g_d$ increases from $0.17 \times 10^{-3} \text{mho}$ to $1.38 \times 10^{-3} \text{mho}$ till the fluence of $25 \times 10^{11} \text{e/cm}^2$ and further decreases to $0.311 \times 10^{-3} \text{mho}$ as increase in the fluence up to $482 \times 10^{11} \text{e/cm}^2$. These results may attribute to the irradiation induced electric field within the oxide in such a way that the density of holes accumulated at the source-end is more than that of the drain-end of Si-SiO₂ interface which result into increase in the fast states. However, at lower electron fluence i.e. up to $25 \times 10^{11} \text{e/cm}^2$, the increasing behavior of $g_d$ is attributed to the trapping of large number of negatively charged fast interface states, responsible in contributing to the current, which results into increase in $g_d$ value. Whereas, at higher electron fluence the decreasing trend of $g_d$ revealed that when MOS structure exposed to the 6MeV energy electrons under bias condition i.e. gate voltage near to the threshold voltage, electron-hole pairs generated throughout the bulk of the SiO₂ layer. These electrons are swept towards the gate electrode, while the holes proceed towards the silicon substrate. Those holes generated in the bulk of the oxide, eventually encounter the distribution of hole traps which assume to start at Si-SiO₂ interface and extend 5 to 10 nm into the oxide. A considerable number of holes gets trapped and remaining continue to travel towards Si-SiO₂ interface through hopping transport process and may assumed to be a rapidly removed by electrons tunneling from the silicon substrate. These traps are effectively empty states. This tunneling process is responsible for the long term annealing of oxide traps and also reason for the decrease in drain conductance.

The variation in $(I_{DS})^{1/2}$ with $V_{gs}$ at different 6MeV energy electron fluences for n-channel depletion MOSFET's under biased at $V_{GS}=-0.9\text{V}$ and $V_{ds}=10\text{mV}$ is shown in Figures 4.12. From figure it is observed that there is sufficient negative shift in the $I_d-V_g$ curve with marginal change in slop of linear region of the curve. This mainly attributes to the small probability of the electrons generated undergo the recombination process with trapped holes.
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Figure 4.10: Variation in drain current ($I_{ds}$) with drain to source voltage ($V_{ds}$) at different 6MeV energy electron fluences for the fixed value of $V_g=-0.9V$ of n-channel depletion MOSFET’s under bias condition.

Figure 4.11: Variation in drain conductance ($g_d$) with different 6MeV energy electron fluences for n-channel depletion MOSFET’s under bias at $V_g=-0.9V$.

Figure 4.12: Variation in ($I_{ds}^{1/2}$) with $V_g$ at different 6MeV energy electron fluences for n-channel MOSFET’s under bias at $V_g=-0.9V$ and $V_d=10mV$. 
At the same time large numbers of induced charges build up in the oxide region, which subsequently develop the positive electric field in the oxide. This field continuously increases till the electrical break down occurs and trapped charges return to the surface. This build up of electric field in the oxide region causes negative shift in \( I_d - V_g \) curve. Quantitatively it can be analyzed on the basis of the parameters such as threshold voltage \( (V_{th}) \) and transconductance \( (g_m) \) respectively. The variation in \( g_m \) and \( V_{th} \) with different 6MeV energy electron fluences for n-channel depletion MOSFET's under bias at \( V_{GS} = -0.9V \) and \( V_{ds} = 10mV \) are shown in Figures 4.13 and Figure 4.14 respectively. From figure it is observed that initially \( g_m \) decreases substantially from \( 0.272 \times 10^{-3} \) mho to \( 0.0345 \times 10^{-3} \) mho till the fluence of \( 122 \times 10^{11} \) e/cm\(^2\), then further decreases gradually as increase in the fluence up to \( 1200 \times 10^{11} \) e/cm\(^2\). This is also due to the radiation induced electron-hole pairs which undergo the process of recombination with the trapped holes. In this process, the generation, injection, trapping and recombination of the charge carrier develops the local electric field in the oxide or at the Si/SiO\(_2\) interface [13-14], which mainly responsible for the decrease in \( g_m \). Moreover, it is also observed from the Figure 4.14 that the threshold voltage increases substantially in the negative direction from -1.1V to -3.35V with increase in the electron fluence. This attributes to the defects lead by negative fixed oxide charges associated with in less than \( \sim 50\AA \), which are mostly contributed in carrier scattering mechanism. Those charges situated at more than 50\AA distance in the bulk of the oxide from the Si-SiO\(_2\) interface consider as oxide charges and are less effective on drain current as compared to the interface fast states. As a result, for higher electron fluence both these parameters found to be decreased due to the generation of oxide charges. In such case usually the **Total Induced Dose** (TID) phenomena in oxide, which is sensitive to the applied bias condition to be observed. As said, radiation induced electron-hole pairs have a probability to recombine that is lowered by an applied electric field. The biasing condition maximized the TID effects; hence it gives the worst possible picture for the device degradation. Variation of \( V_{th} \) due to contribution of interface and oxide trapped charges in n-MOSFET device through trapped holes and tunneling of electrons tends to observed decrease in the threshold voltage. Whereas, small variation in \( V_{th} \) for higher fluence is due to the trapped holes which have a faster dynamic and they prevail at the beginning of the irradiation itself. Then gradually anneal due to the temperature or from generated electrons. At the same time, the interface state accumulates and, as they do not anneal, they finally dominate the threshold voltage shift.
Figure 4.13: Variation in transconductance ($g_m$) with different 6MeV energy electron fluences for n-channel MOSFET's under bias at $V_g$=-0.9V and $V_{ds}$= 10mV.

Figure 4.14: Variation in threshold voltage ($V_{th}$) with different 6MeV energy electron fluences for n-channel depletion MOSFET's under bias at $V_g$=-0.9V.

Figure 4.15: Variation in mobility with different 6MeV energy electron fluences for n-channel MOSFET's under bias at $V_g$=-0.9V.
In some typical case; the trapped holes anneal so fast as a result the threshold voltage shift shows always positive.

The TID phenomenon in MOS transistor under biased condition is directly influenced on the parameter such as mobility. The variation in mobility with different 6MeV energy electron fluences for n-channel depletion MOSFET's under bias condition is shown in Figure 4.15. From figure it is observed that at lower electron fluence, there is reversibly introduce and remove the positive charges near the Si-SiO₂ interface of MOS-structure. As a result, the effective mobility (μ_eff) found to be increased drastically as the sheet carrier concentration increases. It is attributed to both the electron-phonon interaction and the screening of Coulombic scattering mechanism of channel charge carriers. Therefore, the effective mobility increases substantially from 314cm²/V-Sec to 1777cm²/V-Sec up to the fluence of 25×10¹¹e/cm² through fast surface states and further decreases gradually with increase in the fluence. These states are independent of magnitude and polarity of the potential applied during irradiation. For higher electron fluence both the mobilities i.e. field effect and effective mobility decrease due to defects lead by negative fixed oxide charges associated within about 50Å mostly contributed in scattering. The charges present in the bulk of the oxide situated more than the 50Å distance from the Si-SiO₂ interface consider as oxide charges and have low effect on channel carrier charges. These charges increase continuously with increase in the electron fluence by the trapping of holes due to applied voltage and respective polarity to the gate during irradiation.

The integrated surface potential, which affects the carrier mobility become results after cancelling corresponding trapped oxide charges in the gate oxide region. The remaining localized charge distribution would grow much faster than Pb-associated centers. The variation in surface potential with gate voltage at different 6MeV energy electron fluences for n-channel depletion MOSFET's under bias condition is shown in Figure 4.16. From figure it is observed that a function of surface potential coupled with direct measurements of the interface states distribution is obtain by complete interface state distribution of donor and acceptor states in weak inversion region. The relative variation in surface mobility with radiation induced surface potential at different 6MeV energy electron fluences for n-channel depletion MOSFET's under bias condition is shown in Figure 4.17.
It shows that the localized charges are activated at a particular gate voltage which develops the surface potential, where it observes the maximum surface mobility of charge carriers. However, due to irradiation, these charges activate more i.e. at lower electron fluence the oxide charges generate more than interface states, but with further increase in the electron fluence the interface states generated to be more than oxide charges. Therefore, integrated surface potential decreases at higher electron fluence by compensating the oxide and interface states, which mainly responsible to shift positive potential with decrease in mobility.

The net threshold voltage shift, $\Delta V_T$ and its contribution towards interface states, $\Delta V_{Nit}$ and oxide states, $\Delta V_{Not}$ at different 6MeV energy electron fluences for n-channel
depletion MOSFET's under bias condition is shown in Figure 4.18. It is observed that under bias condition seem to lead qualitatively different oxide and interface traps charge buildup and effects on radiation induced annealing behavior of the MOS device.

![Figure 4.18: Net threshold-voltage shift ($\Delta V_{th}$) and it's contributions to that shift due to in interface ($\Delta V_{Ni}$) and oxide ($\Delta V_{No}$) trapped charges at different 6MeV energy electron fluences for n-channel MOSFET's under bias condition.]

Therefore, in this case oxide trapped charges contribute larger voltage shift as compared to interface states. These results mainly attribute to the enhancement of hole-trapping under bias during irradiation is more as compared to generation of interface-states.

Actually, radiation-induced threshold voltage shift due to $N_{ot}$ is basically the difference between the effects of trapping holes and electrons. It is usually causes a net positive space charge in the oxide of MOS device. This is one of the two dominant damage mechanisms of MOS TID radiation effects. From these results it is infer that high-energy electrons generate neutral defects can trap electrons injected in the oxide according to the biasing voltage. It results in to increases in $N_{ot}$ as well with increase in the electron fluence.

4.4.2 Gamma and Bremsstrahlung Irradiation

The analysis of irradiation effects of Co-60 Gamma and Bremsstrahlung radiation on MOS devices are the beginning of the extraction of parameters measured from the output and transfer characteristics in the linear region. The variation in drain current, $I_{ds}$ with $V_{ds}$ at different doses of gamma and bremsstraghhlung radiation for n-channel depletion MOSFET's under gate bias $V_g=-0.9V$ and $V_d=10mV$ are shown in Figures 4.19 and 4.20 respectively.
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Figure 4.19: Variation in drain current ($I_{ds}$) with drain to source voltage ($V_{ds}$) at different doses of Co-60 Gamma radiation for n-channel MOSFET's under bias $V_g$=0.9V and $V_{ds}$=10mV.

Figure 4.20: Variation in drain current ($I_{ds}$) with drain to source voltage ($V_{ds}$) at different doses of bremsstrahlung radiation for n-channel MOSFET's under bias $V_g$=0.9V and $V_{ds}$=10mV.

Figure 4.21: Variation in drain conductance ($g_d$) with different doses of gamma and bremsstrahlung radiation for n-channel MOSFET's under bias $V_g$=-0.9Volt and $V_{ds}$ = +10mV.
From figures it is observed that the saturation drain current and pinch off voltage found to be considerable increased with increase in the dose and also observed to be change in the drain conductance. The variation in drain conductance, $g_d$ with different doses of gamma and bremsstrahlung radiation for n-channel depletion MOSFETs under gate bias $V_g=-0.9$V and $V_d=10$mV is shown in Figure 4.21. It is observed from the figure that in case of gamma irradiation the $g_d$ increases from $0.34\times 10^{-3}$ mho to $1.02\times 10^{-3}$mho with increase in dose form 0 to 28Gy. While, in case of bremsstrahlung irradiation, the $g_d$ also found to be increased from $0.34\times 10^{-3}$ mho to $1.1\times 10^{-3}$ mho with increase in the dose from 0 to 56Gy. It is also observed that the $g_d$ increases more in case of bremsstrahlung radiation than the gamma irradiation. The corresponding transfer characteristics of variation in $I_{ds}$ with gate voltage, $V_g$ at different doses of gamma and bremsstrahlung radiation for n-channel MOSFET’s under bias at $V_g=-0.9$V and $V_d=10$mV are shown in Figures 4.22 and 4.23 respectively. It is observed from the figures that in both the cases a well distinguished shift in $I_{ds}$-$V_g$ curve found along the higher voltage in the negative direction with marginal decrease in slope of the linear region. Its degradation has been analyzed by measuring the transconductance, $g_m$ and threshold voltage, $V_{th}$ at different doses of gamma and bremsstrahlung radiation for n-channel depletion MOSFET’s under gate bias $V_g=-0.9$V and $V_d=10$mV which are shown in Figures 4.24, 4.25 respectively. These negative shifts in I-V curves are mainly attributed to the additional effect of larger vertical electric field induced due to irradiation. When device goes under gamma or bremsstrahlung radiation, the electron-hole pairs are generated throughout the insulator layers, and a fraction that escaped initial recombination yields as a free electrons and holes. These free charge carriers are swept by electric field and some of them are captured by the charge trap centers. The amount of captured charge depends on the local density and capture cross section of the trap centers. Here, an increase in drain current is due to fast negatively charged interface states, which are mostly considered as donor type. When we apply small drain voltage, these states provide a large amount of current in the output characteristics even for small gate voltage. But, corresponding oxide states and slow interface states influenced to decrease in transconductance ($g_m$) and threshold voltage ($V_{th}$). A typical threshold voltage shift, $\Delta V_T$ and its contribution towards interface $\Delta V_{Nit}$ and oxide $\Delta V_{Not}$ states; at different doses of bremsstrahlung radiation for n-channel depletion MOSFET's under gate bias $V_g=-0.9$V and $V_d=10$mV is shown in Figure 4.26.
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Figure 4.22: Variation in $\left(I_{ds}\right)^{1/2}$ with $V_g$ at different doses of gamma radiation for n-channel MOSFET’s under bias at $V_g=-0.9V$.

Figure 4.23: Variation in drain current ($I_{ds}$) with $V_g$ at different doses of bremsstrahlung radiation for n-channel MOSFET’s under bias at $V_g=-0.9V$ and $V_{ds}=+0.2V$.

Figure 4.24: Variation in transconductance ($g_m$) with different doses gamma and bremsstrahlung radiation for n-channel MOSFET’s under bias at $V_g=-0.9V$ and $V_{ds}=+10mV$. 
It is observed from the figure that under bias condition seem to lead quantitatively large voltage shift due to oxide trapped charges as compared to interface trapped charges. The contribution of oxide states found to be continuously increased up to 1.41V and no turnaround effect is observed. In the same case, contribution of interface states found to be very small i.e. up to 0.6Volt for 98Gy dose of bremsstrahlung radiation. Further increase in the dose contribution of interface states become saturates and only oxide states shifted to roll out in threshold voltage. These results are mainly attributed to the theory presented by Stern and Howard for shift in threshold voltage. They have shown that positive oxide trapped ions near the interface result in bound states. As per their prediction the binding energy should decrease as free-electron density increases because of increased screening.

![Figure 4.25](image1.png)

**Figure 4.25:** Variation in threshold voltage (V\text{th}) with different doses of gamma and bremsstrahlung radiation for n-channel MOSFET's under bias at V\text{\textsubscript{bg}}=-0.9V and V\text{ds}=+10mV.

![Figure 4.26](image2.png)

**Figure 4.26:** Net threshold-voltage shift (ΔV\text{th}) and contributions to that shift due to interface (ΔV\text{Nit}) and oxide (ΔV\text{Not}) trapped charges at different doses of bremsstrahlung radiation for n-channel MOSFET's at V\text{\textsubscript{bg}}=-0.9V and V\text{d}=+10mV.
At some electron density, the binding energy would be small enough so that the electrons would be released and contributed in current. Radiation induced charge components corresponds to slow interface states and are very close to Si-SiO\textsubscript{2} interface, so that charging and discharging are possible but only with very long time constants. These are compared with fast interface states, which can exchange charge with the valence and conduction bands in silicon during C-V measurement. The variation in capacitance (C) with gate voltage (V\textsubscript{g}) at different doses of gamma and bremsstraghlung radiation for n-channel depletion MOSFET's under gate bias V\textsubscript{g}=-0.9V and V\textsubscript{d}=10mV are shown in Figures 4.27(a) and (b). From figures it is observed that shift in curves toward higher negative gate voltage corresponds to the charge exchange process with slow states. This is caused by the charging and discharging of slow states at the interface. They are donor type states, which mean they are neutral when filled with electrons and positively charged when empty. It must also be pointed out that these positive charges in the slow states are different from trapped holes observed due to radiation in the oxide. Negative shift in lower portion of the C-V curve revealed that there is generation of certain amount of slow states generated together with trapped holes. But, all the positive charge is interpreted as a trapped holes only [15, 16]. The variation in effective density of oxide charges (\Delta Q\textsubscript{ox}) with different doses of gamma and bremsstraghlung radiation for n-channel depletion MOSFET's under bias at V\textsubscript{g}=-0.9V and V\textsubscript{d}=10mV is shown in Figure 4.28. From figure it is observed that the \Delta Q\textsubscript{ox} found to be increased with increased in the dose. This attributes to the net charges induced in the oxide during irradiation depends on the self-trapped electron and hole concentration. Particularly, the concentration of self-trapped holes created in the bulk of SiO\textsubscript{2} could be very large i.e. in the range of $10^{12}$ due to gamma and bremsstraghlung irradiation under bias condition. This trapping phenomena followed by two types of process (1) hole trapped in the 2p orbital of a normal bridging oxygen (2) hole tunneling between valence-band states on a pair of neighboring oxygen sites. These two types of defects should contribute greatly to hole trapping by irradiation. They could be the origin of the net positive charge in the gate oxide, which may be contributed in the shift in flat band, mid gap and threshold voltage along with slow interface states. The variation in threshold voltage (V\textsubscript{th}), flat band voltage (V\textsubscript{fb}) and mid gap voltage (V\textsubscript{mg}) with different doses of bremsstraghlung radiation for n-channel depletion MOSFET's under bias at V\textsubscript{g}=-0.9V and V\textsubscript{d}=10mV is shown in Figure 4.29.
Figure 4.27(a): Variation in capacitance (C) with gate voltage ($V_g$) at different doses of gamma radiation for n-channel MOSFET's under bias at $V_g$=-0.9V and $V_d$=+10mV.

Figure 4.27(b): Variation in capacitance (C) with gate voltage ($V_g$) at different doses of bremsstrahlung radiation for n-channel MOSFET's under bias at $V_g$=-0.9V and $V_d$=+10mV.

Figure 4.28: Variation in oxide ($\Delta Q_{ot}$) with different doses of bremsstrahlung radiation for n-channel MOSFET's under bias at $V_g$=-0.9V and $V_d$=+10mV.
Figure 4.29: Variation in threshold voltage shift (V), flat band voltage (V_{fb}) and midgap voltage (V_{mg}) with different doses of bremsstrahlung radiation for n-channel MOSFET's under bias at V_g=-0.9V and V_d=+10mV.

It is observed that such large negative shift in these parameters are due to the amount of trapped electrons at Si-SiO_2 interface is smaller than that of trapped hole. It means that the amount of generated electron in the oxide is smaller than the amount of generated hole in the oxide. In case of negative V_g, the saturation of shift in parameters with increasing dose is not observed. This indicates that oxide field does not reach zero during irradiation due to large holes captured at Si-SiO_2 interface. From these results, it is considered that the capture cross section of hole traps at interface is smaller than that of electron traps at the interface. This process induced the surface charge density at the interface, which further confirmed and analyzed using conductance method. The variation in conductance (G_m) with gate voltage at different doses of bremsstraghlung radiation for n-channel depletion MOSFET's under bias at V_g=-0.9V and V_d=10mV is shown in Figure 4.30. It is observed from the figure that the conductance curve shifts toward higher negative gate voltage with increase in the dose. Moreover, it is also found to be increased in with increase in broadening of the curve from accumulation to inversion region. These conductance results support the analysis of I-V and C-V results, where it describes the increase in positive charges in the oxide as compared to interface states. Such positive states are corresponding to the surface states in the oxide, which mainly responsible to enhance the negative gate voltage to achieve same conductance. The variation in surface charge density (Q_{ss}) with different doses of V_g=-0.9V and V_d=10mV is shown in Figure 4.31.
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Figure 4.30: Variation in conductance ($G_m$) with gate voltage ($V_g$) at different doses of bremsstrahlung radiation for n-channel MOSFET's under bias at $V_g$=-0.9V and $V_{ds}$=+10mV.

Figure 4.31: Variation in Surface charge density ($Q_{ss}$) with different doses of gamma and bremsstrahlung radiation for n-channel MOSFET's under bias at $V_g$=-0.9V and $V_{ds}$=+10mV. gamma and bremsstrahlung radiation for n-channel depletion MOSFET's under bias at

It is observed that surface charge density, $Q_{ss}$ increases from $1.33 \times 10^{10} \text{cm}^{-3}$ to $3.8 \times 10^{10} \text{cm}^{-3}$ as increase in gamma radiation dose from 0 to 56Gy and 0.6$\times$10$^{10}$cm$^{-3}$ to 4$\times$10$^{10}$cm$^{-3}$ as increase in bremsstrahlung radiation dose from 0 to 138Gy. The $Q_{ss}$ observed to be more in case of gamma irradiation than bremsstrahlung irradiation because of larger capture cross section of the trap centers.
4.4.3 Heavy Ions

The study of effects of high energy swift heavy ions on n-MOSFETs under bias condition is very important for the space applications. Typical $I_D-V_{DS}$ and $I_D-V_G$ characteristics at different 100MeV silver ion fluences for n-channel depletion MOSFETs under bias at $V_g=-0.9$V and $V_d=10$mV are shown in Figures 4.32 and 4.33 respectively. It is observed from the figures that there is substantial decrease in $I_d$ from 4.04mA to 39.7$mA$ and pinch-off voltage from 5.2V to 0.65mV. Whereas the $g_d$ and $g_m$ found to be decreased from 1.21mho to 0.066$mA$mho and $215\times10^{-3}$mho to $3.19\times10^{-3}$mho respectively with increase in the ion fluence. These results are mainly attributed due to the increase in coulomb scattering between the ion induced interface trapped charges and free carriers in the channel. When the 100MeV energy $Ag^{5+}$, $Ni^{7+}$ and $I^{10+}$ ions pass through the MOS device, they produce ionization or bond breaking event and atomic displacements along their paths. Some of the ion induced electron-hole pairs quickly undergo recombination, therefore these are not available for any further radiation effects and some of the positively charged holes undergo a slow dispersive transport towards the Si/SiO$_2$ interface and trapped at interface. As drain voltage is applied to MOS device, very small current have been measured due to negligible electron trapping at interface because the capture cross-section of electron traps is very small but most of electron captured in holes and scattered by the interface states. The variation in threshold voltage, $V_{th}$ with different 100MeV energy I, Ni and Ag ion fluences for n-channel depletion MOSFET's under bias at $V_g=-0.9$V is shown in Figure 4.34. It is observed from the figure that small negative shift in the threshold voltage is observed in case of iodine and nickel ions from -1.2V to -1.8V and -1.2V to -1.6V for fluences of $1\times10^9$ ion/cm$^2$ and $5\times10^9$ion/cm$^2$respectively. Further increase in the fluence there is positive shift in $V_{th}$ and shows the rebound effect for fluence of $10\times10^9$ion/cm$^2$ and recovered almost up to -0.09V, +1.62V and +2.45V respectively for Ag, I and Ni ions. These results are attributed to the difference in electronegativity of the respective ion species, i.e. the electronegativity of Iodine is 2.66 which is large as compared to Ni and Ag ions. The nickel and silver ions have nearly same electronegative values i.e. 1.91 and 1.93 respectively. Moreover, an additional oxide charges ($N_{ox}$) are induced by energetic ion, which mainly located at or near the interface and annealed by electron tunneling from channel. As the oxide trapped charges are completely neutralized, the net $\Delta V_{th}$ shift is entirely due to interface state charges.
Figure 4.32: Variation in drain current ($I_{ds}$) with drain to source voltage ($V_{ds}$) at different 100MeV energy silver ion fluences for n-channel MOSFET's under bias at $V_g=-0.9V$ and $V_d=+10mV$.

Figure 4.33: Variation drain current ($I_{ds}$) with gate voltage ($V_g$) at different 100MeV silver ion fluences for n-channel MOSFETs under bias at $V_g=-0.9V$ and $V_d=+10mV$.

Figure 4.34: Variation in threshold voltage ($V_{th}$) with different 100MeV energy Iodine, Nickel and Silver fluences for n-channel MOSFET’s under bias at $V_g=-0.9V$ and $V_d=+10mV$. 
It is speculated that as a result of low fluence of ion irradiation, either directly or due to the capture of holes, defect created in the oxide region has positive charge. However, for higher ion fluence, the trapped positive charges saturate and produce more Coulombic force on electron to recombine the large amount of trapped holes. A typical result of the shift in trapped density of interface ($\Delta N_{it}$) and oxide ($\Delta N_{ot}$) states with different 100MeV energy silver ion fluences for n-channel depletion MOSFET's under bias at $V_g=-0.9V$ is shown in Figure 4.35. It is observed from the figure that the magnitude of oxide and interface states found to be increased with same rate up to the ion fluence of $1\times10^9$ion/cm$^2$. Further increase in the fluence density of oxide charges observed to be changes marginally and saturates, but density of interface states found to be increased continuously. It is also observed that final value of the shift in threshold voltage depends on $\Delta V_{Nit}$ and rebound effects can be predicted by measuring the density of interface states. Because, n-channel MOS-device has approximately 0.9V work function, so that a built-in electric field exists in the oxide with an externally applied gate voltage. This field is strong enough to produce sizable hole yield, but not strong enough to significantly reduce the hole capture cross section at the interface. The heavy ion produce positive space charge which compensates the built-in electric field and decrease the probability of hole trapping yield through increasing geminate recombination. Some of the electrons generated due to irradiation are pulled the hole space charge and annihilate the trapped holes and generate interface states. So the MOS device irradiated under ‘on’ state makes hole continuously be trapped and annihilated and generate interface states. Eventually the interface states density can be greater than the trapped hole density, which in turn responsible to have the net positive threshold voltage shift.

The densities of oxide and interface states measured from subthreshold current method have also been confirmed using Capacitance-Voltage measurement at 1MHz frequency. Typical, variation in capacitance (C) with applied gate voltage ($V_g$) at different 100MeV energy silver ion fluences for n-channel depletion MOSFET's under bias at $V_g=-0.9V$ is shown in Figure 4.36. It is observed that the C-V curve shifts towards higher negative gate voltage with increase in the ion fluence. The measured values of shift in C-V curve at typical capacitance i.e. 10pF is from -0.7V to -0.78V for the ion fluence of $1\times10^9$ion/cm$^2$ and further increase in the ion fluence C-V curve shift towards higher positive gate voltage and reaches up to the +2.67V. The same C-V curves have been used to calculate the Flat band Voltage ($V_{FB}$) and oxide capacitance ($C_{OX}$) for MOSFET under bias condition and the respective result is shown in Figure 4.37.
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Figure 4.35: Net shift in density of interface and oxide states ($\Delta V_{Nit}$) and ($\Delta V_{Not}$) with different 100MeV energy Ag ion fluences for n-channel MOSFETs under biased at $V_g$=-0.9V and $V_d$=+10mV.

Figure 4.36: Variation in capacitance (C) with gate voltage ($V_g$) at different 100MeV Silver ion fluences for n-channel MOSFET’s under bias at $V_g$=-0.9V and $V_d$=+10mV.

Figure 4.37: Variation in flat band voltage ($V_{fb}$) with different 100MeV energy Iodine, Nickel and Silver ion fluences for n-channel MOSFET’s under bias at $V_g$=-0.9V and $V_d$=+10mV.
It is observed from the figure that initially $V_{FB}$ found to be increased in the negative direction from -0.81V to -1.21V up to the ion fluence of $1\times10^9$ion/cm$^2$. Further increase in the fluence, $V_{FB}$ shows turnaround and rebound effects. The magnitude of flat band voltage for iodine ion is observed to be greater than that of Ag and Ni ions. Such results may be attributed due to the electronic and nuclear energy loss by iodine ions is more as compared to Ag and Ni ions as shown in Table 4.1. Iodine ion deposits more energy and produce charge in the oxide as compared to that of Ni and Ag ions. However, the energy deposited due to the nuclear collisions displaces the silicon and oxygen atoms at the Si-SiO$_2$ interface which lead to an increase in the trapped negative charge buildup as compared to the bulk SiO$_2$. The variation in oxide state charge density ($Q_{ox}$) with different 100MeV energy Iodine, Nickel and Silver ion fluences for n-channel depletion MOSFET’s under bias at $V_g$=-0.9V is shown in Figure 4.38. It is observed from the figure that $Q_{ox}$ found to be increased with the ion fluence. However, $Q_{ox}$ observed to be more in I and Ag than the Ni ion irradiation.

The corresponding surface charge densities, $Q_{ss}$ have been measured using conductance method. Typical, variation in conductance ($G_m$) with gate voltage ($V_g$) at different 100MeV energy Ag ion fluences for n-channel depletion MOSFET’s under bias at $V_g$=-0.9V is shown in Figure 4.39. It is observed from figure that ion induces positive charge in the oxide close enough to the border. Later, these trapped positive charge may be neutralized by substrate/channel electrons or migrate in deeper position, where its effect is neutralized. It may leave neutral defects close to the interface, which may easily trap channel electron becoming negatively charged and act as new scattering centers for channel electrons, locally reducing the carrier mobility. Again, these defects may trap electrons from the channel and act as interface traps due to bias, which is responsible to produce a positive shift in G-V curve. This process also enhances the surface charge density. The variation in surface charges density ($Q_{ss}$) with different 100MeV energy Iodine, Nickel and Silver ion fluences for n-channel depletion MOSFET’s under bias at $V_g$=-0.9V is shown in Figure 4.40. It is observed from the figure that $Q_{ss}$ increases with the ion fluence. But, in case of nickel ion it saturates for the fluence of $12\times10^{10}$ion/cm$^2$, while in case of iodine and silver ions $Q_{ss}$ observed to be continuously increased with increase in ion fluence. This attributes to the field develop across the gate oxide in the presence of negative gate voltage. The charges induced by ions are separated by the field and then precedes the holes migrating towards the Si-SiO$_2$ interface and the electrons towards the drain.
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Figure 4.38: Variation in oxide states ($Q_{ox}$) with different 100MeV energy Iodine, Nickel and Silver ion fluences for n-channel MOSFETs under bias at $V_g = -0.9V$ and $V_d = +10mV$.

Figure 4.39: Variation in conductance ($G_D$) with gate voltage ($V_g$) at different 100MeV Silver ion fluences for n-channel MOSFET's under bias at $V_g = -0.9V$ and $V_d = +10mV$.

Figure 4.40: Variation in Surface charge density ($Q_{ss}$) with different 100MeV energy Iodine, Nickel and Silver fluences for n-channel MOSFET's under bias at $V_g = -0.9V$ and $V_d = +10mV$. 
Therefore, the movement of these entire excess regions i.e. between the negative surface state density and hole-diffusion may permit a dangerously large electric field in the oxide. It exceeds the critical field and can lead to a localized gate rupture [17].

4.5 Conclusion

Ionizing radiation mainly generates e/h pairs in the silicon dioxide region. The generated electrons are rapidly swept out of the oxide by the applied field, but a fraction of the holes are permanently trapped producing a negative threshold voltage shift. The effects on the parameters vary with the magnitude and polarity of the gate bias during irradiation. Overall, results for positive gate bias show a large threshold voltage shift, since the holes are trapped near the silicon surface where they will exert maximum influence on the MOSFET. Results also show that TID mechanism depends on the electric field because of 1) radiation induced charge yield; 2) the transport of radiation-induced electrons, holes and 3) the capture cross section for trapping and detrapping of radiation-induced electrons and holes.

The results on the effects of 6MeV energy electron on MOSFET’s under bias condition show that a) 6MeV energy electron induces an unstable positive charge in the oxide producing a large negative shift of threshold voltage under bias condition. In some cases at higher electron fluences, the threshold voltage shows turnaround and rebound effects. b) Negative charges in the oxide bulk is not directly generated by electron irradiation, but it derives from electrons injected during the electrical measurement and captured in traps created by the ionizing radiation. c) Donor-type border traps have been observed at both oxide interfaces. The border traps at the gate (silicon) interface can be positively charged after positive biasing and are neutralized after negative biasing. This conclusion shows that contribution of $N_{it}$ and $N_{ot}$ are responsible to shift in threshold voltage and other parameters such as drain conductance, transconductance etc.

The results on the effects of gamma and bremsstrahlung on MOSFET’s under bias condition show that a) The $I_{ds}$-$V_g$ curves observed to be shifted towards more negative gate voltage with increase in dose. b) High and low-level output voltages hardly changed, but $V_{th}$ seriously gets affected. The reason for the small change in high and low-level output voltages is that very small current flows in the device gate and the change of channel resistance hardly affected the output voltage. c) Oxide trapped charges are responsible to shift in negative voltage and same is also confirmed in C-V measurement.
The increase in trapped positive charge in the oxide causes to have parallel shift of the curve to more negative voltages and increase in interface trap density causes to have stretch-out voltage of the curve. d) The contribution of positive oxide trapped charge is more as compared to the negative interface states, therefore, did not show any rebound effects. e) Moreover, shift in $\Delta V_{N_{off}}$ is smaller in case of bremsstrahlung radiation than that of gamma radiation under bias condition.

The results on the effects of 100MeV Ni$^{+7}$, I$^{+10}$ and Ag$^{+5}$ ions on MOSFET’s under bias condition show that a) Higher LET and electronegative values of the respective ions species show more oxide state density than interface state density. b) The bias just near $V_{TH}$ shows C-V curve shifts towards the positive gate voltage indicating the introduction of a large negative space charge into the oxide and/or interface states.

Therefore, overall it is concluded that the change in the parameters of the MOS device under bias occurs mainly due to the contribution of oxide and interface states.
4.6 References