

A comparison of 4 MeV Proton and Co-60 gamma irradiation induced degradation in the electrical characteristics of N-channel MOSFETs



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ABSTRACT

N-channel depletion MOSFETs were irradiated with 4 MeV Proton and Co-60 gamma radiation in the dose range of 100 krad(Si) to 100 Mrad(Si). The electrical characteristics of MOSFET such as threshold voltage (V_{th}), density of interface trapped charges (ΔN_{it}), density of oxide trapped charges (ΔN_{ot}), transconductance (g_m), mobility (μ), leakage current (I_L) and drain saturation current ($I_{D Sat}$) were studied as a function of dose. A considerable increase in ΔN_{it} and ΔN_{ot} and decrease in V_{th} , g_m , μ , and $I_{D Sat}$ was observed after irradiation. The results of 4 MeV Proton irradiation were compared with that of Co-60 gamma radiation and it is found that the degradation is more for the devices irradiated with 4 MeV Protons when compared with the Co-60 gamma radiation. This indicates that Protons induce more trapped charges in the field oxide region when compared to the gamma radiation.

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1. Introduction

Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) are extensively used in space, military and other radiation rich environments such as Large Hadron Collider (LHC) applications due to their faster switching speed and simple way of operation when compared to bipolar transistors [1–5]. Space is unquestionably an extreme environment where the variations in physical parameters such as temperature, intensity of radiations are drastic and thus, it is very hard to operate the microelectronics. Ever since the first satellite has launched, it has been long standing concern that the particles originating from the solar events such as solar flares, coronal mass ejection and galactic cosmic rays, strike the semiconductor devices and cause accumulation of charges at the sensitive interfaces which will degrade the MOSFET performance and eventually make the device malfunction [2]. This degradation is due to the generation of oxide trapped charges in the oxide layer and interface traps at the Si/SiO₂ interface. When the ionizing radiation is incident on the MOS devices, it creates electron–hole pairs. When positive bias is applied to the gate terminal, since the electrons have high mobility in SiO₂, they can easily sweep out into the external circuit. Whereas the holes have lower mobility thus,

they drift very slowly towards the Si/SiO₂ interface, where a fraction of them get trapped and induce oxide trapped charges [6–11]. These positive trapped charges induce a negative shift in the threshold voltage of the MOS devices which increases the leakage current and hence power consumption will also increases. During the hole transport and trapping processes, hydrogen is released within the oxide, and may be transport to the interface and react with the silicon dangling bonds and thus forming interface traps. The density of these interface traps is greatly enhanced by the positive bias applied at the gate during the irradiation and they too degrade the device by decreasing the transconductance (g_m) and mobility (μ) [12–15]. In order to use MOS devices in deep space applications, the devices need to withstand few krad to few Mrad of gamma equivalent total dose but for high energy physics experiments like in Large Hadron Colliders (LHCs), the devices need to withstand 1 MeV equivalent $1 \times 10^{16} \text{ cm}^{-2}$ fluence of neutron or 100 Mrad of total dose in their five year life time [21]. Hence the electronics and materials used in the radiation rich environments should be radiation hard to operate over mission lifetime. The most important effects against which the satellite should be radiation hard are total dose, displacement damage and single event effect (SEE) [16]. When the ionizing particles pass through the device material, they lose their energy by electronic and nuclear interactions. The energy deposited by the particle per unit mass is known as total dose, the deposited energy may displace the atoms present

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in the lattice which is known as displacement damage. When a single ionizing particle passes through a material, it creates a burst of electron–hole pairs along its trajectory which causes a detrimental effect on the circuit and it is known as the single event effect.

The main objective of this paper is to study the long term effects such as the total dose effects and displacement damage. Thus only protons and gamma radiations were considered as an input in this study. Because other particles such as solar heavy ions and galactic cosmic rays do not play a significant role while studying the long term radiation effects in space due to their lower fluxes. This is true only for the orbits which lie above the lower earth orbits [16]. Thus, in the present paper we systematically compared the total dose response of the N-channel MOSFETs for the 4 MeV Protons and Co-60 gamma radiations on ΔV_{th} , ΔN_{it} , ΔN_{ot} , I_L , g_m , μ , and I_{Dsat} under the floating condition.

2. Experiment

The present experiment is carried out using two serially connected N-channels with independent dual gate depletion MOSFETs (BEL 3N187) with isolated silicon substrate ($<100>$ 4–11 ohm cm of thickness $\sim 650 \mu\text{m}$) and the gate oxide thickness (SiO_2) $\approx 0.75 \mu\text{m}$. The gate metal (Al) thickness is $\approx 1.2 \mu\text{m}$ and the device channel size is $\approx 1.2 \times 5 \mu\text{m}^2$. The cross sectional view of N-channel MOSFET is shown in Fig. 1 [31]

The N-channel MOSFETs were exposed to 4 MeV Protons at 3 MV tandem Pelletron accelerator at Institute of Physics (IOP), Bhubaneswar, India. The MOSFETs were irradiated with Proton fluence ranging from 9×10^{10} to 9×10^{13} protons/cm² at room temperature in an experimental chamber maintained at 10^{-6} torr. The gamma equivalent dose for the above mentioned fluence has a range of 100 krad(Si) to 100 Mrad(Si) respectively. The fluence on the MOSFET was determined by integrating the total charge accumulated on the MOSFET using a current integrator and then counting by a scalar meter. The Proton beam was scanned over the samples in an area of $5 \times 5 \text{ mm}^2$ by a magnetic scanner in order to get the uniform fluence. The irradiation was carried out in vacuum when the MOSFETs were under grounding condition. The typical beam current during irradiation was $\approx 20 \mu\text{A}$. The Co-60 gamma irradiation was done using gamma chamber with a dose rate of 167 rad/s at Pondicherry University for the same dose range of 100 krad(Si) to 100 Mrad(Si) at room temperature.

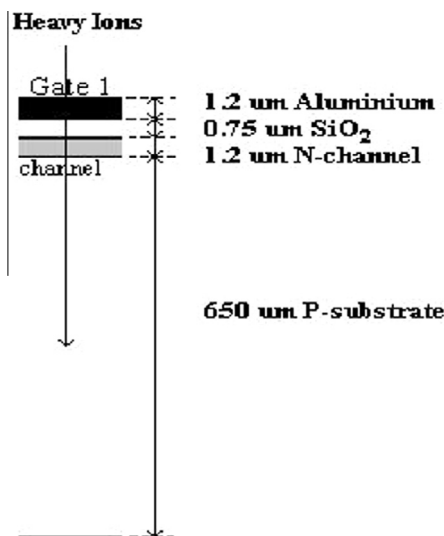


Fig. 1. Cross sectional view of N-channel MOSFET (BEL 3N187).

The electrical characterization of MOSFETs was done before and after irradiation using a computer interface Keithley dual channel source meter model 2636A. Using the transfer characteristics i.e., a graph of drain current (I_D) versus gate voltage (V_{GS}) the threshold voltage is determined by using one of the methods available [22], which is to choose a current level and to find the corresponding gate voltage required to produce that current. Here, in this work we have chosen $1 \mu\text{A}$ as the current and defined the gate voltage required to produce that drain current as the threshold voltage (V_{th}). The transconductance (g_m), was also extracted from the transfer characteristics at constant drain to source voltage $V_{DS} = 0.1 \text{ V}$. The mobility (μ) was determined from the g_{mpeak} values at constant $V_{DS} = 0.1 \text{ V}$. The drain saturation current (I_{Dsat}) was determined using the output characteristics i.e., the graph of drain current (I_D) versus drain to source voltage (V_{DS}) measured at different gate bias.

3. Results and discussion

The incident radiation when passes through a material, it loses its energy by two processes namely, electronic energy loss, $<dE/dX>e$ and nuclear energy loss $<dE/dX>n$. We have used SRIM-2008 [17,18] simulation program to estimate the value of $<dE/dX>e$, $<dE/dX>n$ and range of 4 MeV Proton in the metal oxide semiconductor (MOS) device structure. From the simulation it is found that for 4 MeV Proton, the value of $<dE/dX>e = 0.06906 \text{ MeV cm}^2 \text{ mg}^{-1}$ and $<dE/dX>n = 4.010 \times 10^{-5} \text{ MeV cm}^2 \text{ mg}^{-1}$ and it is observed that the electronic energy loss is greater than the nuclear energy loss (three orders of magnitude) in the silicon due to larger elastic scattering cross-section. Hence, all the energy deposited to the matter is mainly due to the electronic energy loss during the early passage of ions into the material. The nuclear energy loss becomes dominant near the end of ion range and this produces point defects and collision cascades. SRIM simulations reveals that the 4 MeV Protons can pass through the Al gate, SiO_2 and Si substrate and get implanted inside the p-silicon substrate at a depth of $148.3 \mu\text{m}$ and the LET of 4 MeV Protons in Si is $0.069 \text{ MeV cm}^2 \text{ mg}^{-1}$. The 4 MeV Protons generate the electron–hole pairs and some undergo recombination and are not available for any electrical transport. Whereas some of the holes make slow dispersive transport towards the Si/SiO₂ interface where they get trapped in deep hole traps. The microscopic origin of the dispersive transport is likely to be multiple trapping and detrapping of the holes or hopping of holes through shallow traps. This results in additional oxide charges (N_{ot}) and reduces the threshold voltage (V_{th}). Since the capture cross-section of electrons in SiO_2 is very small (by a factor of 10^4), the probability of trapping of electrons in oxide layer is negligible [19]. However this process competes with the electron–hole recombination process and gives rise to charge yield which is a fraction of radiation induced electrons and holes which survived initial recombination [33–36]. Depending on the LET of the incident radiation, the charge yield in SiO_2 can be estimated by the two known models, columnar model and geminate model. The columnar model is applicable when the LET of the particle is greater than $0.1 \text{ MeV cm}^2 \text{ mg}^{-1}$. Whereas the geminate model is applicable when the LET of the particle is much less than $0.01 \text{ MeV cm}^2 \text{ mg}^{-1}$. Since the LET of the 4 MeV Protons used in this work is $0.069 \text{ MeV cm}^2 \text{ mg}^{-1}$ neither of the above models are applicable.

It is well known that the Co-60 gamma radiation produce radiation damage via the creation of Compton electrons, which results in the charge deposition at Si/SiO₂ interface and the nearby oxide layer. By analyzing silicon displacement cross-section for electrons and the secondary electron spectrum in a Co-60 source for electron energies ranging from 0.2 to about 1.0 MeV, equivalent

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