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A comparison of 48 MeV Li^{3+} ion, 100 MeV F^{8+} ion and Co-60 gamma irradiation effect on N-channel MOSFETs

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ABSTRACT

N-channel MOSFETs were irradiated by 48 MeV Li^{3+} ions, 100 MeV F^{8+} ions and Co-60 gamma radiation with doses ranging from 100 krad to 100 Mrad. The threshold voltage (V_{TH}), voltage shift due to interface trapped charge (ΔV_{Nit}), voltage shift due to oxide trapped charge (ΔV_{Not}), density of interface trapped charge (ΔN_{it}), density of oxide trapped charge (ΔN_{ot}), transconductance (g_m), mobility (μ) of electrons in the channel and drain saturation current ($I_{D\ Sat}$) were studied as a function of dose. Considerable increase in ΔN_{it} and ΔN_{ot}, and decrease in V_{TH}, g_m and $I_{D\ Sat}$ were observed in all the irradiated devices. We correlated the degradation of μ with the ΔN_{it} and the effect of ΔN_{ot} is found to be negligible for degrading the μ. The maximum degradation was observed for the devices irradiated with Co-60 gamma radiation when compared with those irradiated with ions, since gamma radiation can generate more trapped charge in field oxide when compared to the high energy ions.

1. Introduction

The metal oxide semiconductor field effect transistors (MOSFETs) are fundamental components in advanced integrated circuits (ICs) and are used in space, military and other radiation rich environments like large hadron collider (LHC) applications because of their faster switching speeds and simple drive requirements. However, MOS and bipolar devices are sensitive to radiation and are prone to parametric or even functional failure on exposure to ionizing radiations [1–5]. The basic damage effects of ionizing radiation in MOS devices results from the generation of electron–hole pairs in the gate oxide. When positive bias is applied to the gate, electrons drift rapidly under the influence of the applied electric field and most flow out into the external circuit. In this case holes have been shown to have lower mobility and drift slowly to the Si/SiO_2 interface, a fraction get trapped and thus forming the radiation induced oxide trapped charge [6–8]. These positive charges induce a negative shift in the threshold voltage and increase the leakage current, which leads to increased power consumption. During the hole transport and trapping processes, hydrogen is released within the oxide, and may be transported to the interface and react with silicon dangling bonds, forming interface traps. The density of these interface states is greatly enhanced by the positive bias voltage applied during the irradiation and they too can modify the overall charge dependent properties of MOS devices including the decrease in g_m and μ [9–12]. In many applications, particularly in mixed signal and digital technologies the parameter g_m will affect the speed and output drive. The degradation of room temperature g_m from total dose has been studied extensively and is attributed to mobility degradation from increased interface traps [13–15]. A few other investigators have observed degradation of g_m from total dose at lower temperature and showed that both ΔN_{it} and ΔN_{ot} can modulate the resistivity and hence alter the value of g_m [16–19]. In order to use MOS devices in space, the devices need to withstand few krad to few megarad 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 $1\times10^{16}\,cm^{-2}$ fluence of neutron or 100 Mrad of total dose in their five year lifetime. The irradiation times needed to reach in case of high hadron fluences (proton, neutron, pion) at the current proton or gamma irradiation facilities have correspondingly increased. A possible way to decrease the irradiation times to more practical values could be to irradiate devices with energetic heavy ions, taking advantage of the large non-ionizing energy-loss, which significantly increases with the atomic number of the impinging ions. Therefore, the comparison of the effects of high energy ions on MOSFETs with Co-60 gamma radiation is essential in addition

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to basic understanding of the effects of high energy ions on MOS devices. Previously we reported the effects of 8 MeV electron irradiation on MOSFETs irradiated at different gate bias [5], and also the effects of 95 MeV oxygen ion irradiation [20]. The V_{TH} of the irradiated MOSFET was found to decrease significantly after irradiation. The ΔN_{it} and ΔN_{ot} were found to increase after irradiation. In the present work, we present, for the first time, a systematic comparison of 48 MeV Li^{3+} ions, 100 MeV F^{8+} ions and Co-60 gamma irradiation on the V_{TH}, g_m and μ of N-channel depletion MOSFETs in the dose range 100 krad–100 Mrad irradiated at gate bias, $V_{GS}=+2$ V. From the subthreshold measurements the ΔN_{it} and ΔN_{ot} were estimated. Further, the μ in the channel was estimated from the g_{mpeak} and mobility degradation is correlated with ΔN_{it}. The mobility degradation co-efficient due to interface traps (α_{it}) and oxide-trapped charge (α_{ot}) is also estimated and the results obtained are presented and discussed in this paper.

2. Experiment

The two serially connected N-channels with independent dual gate depletion MOSFETs (BEL 3N187) with isolated silicon substrate (<100> 4–11 Ω cm of thickness ~650 μm) and the gate oxide thickness (SiO_2) ≈ 750 ± 50Å were used in the present study [5]. The gate metal (Al) thickness is ≈ 1.2 μm while the device channel size is ≈ 1.2 × 5 μm². Special back-to-back diodes are diffused directly into the MOS pellet and are electrically connected between each insulated gate and the MOSFET source in order to avoid excess or transient voltage. The N-channel MOSFETs were exposed to 48 MeV Li^{3+} ions and 100 MeV F^{8+} ions at the 15 UD 16 MV Pelletron Tandem Van de Graff Accelerator at Inter University Accelerator Center (IUAC), New Delhi, India [21]. The MOSFETs were irradiated with ion fluence from 1.41×10^9 to 1.48×10^{13} ions/cm² at 300 K in an experimental chamber of diameter 1.5 m maintained at 10^{-7} mbar vacuum. The gamma equivalent dose for the above mentioned fluence is ranging from 100 krad to 100 Mrad. The fluence on the sample kept in cylindrical secondary electron suppressed geometry was estimated by integrating the total charge accumulated on the sample using a current integrator and then counting by a scalar meter. The ion beam was scanned over the samples in an area of 10 × 10 mm² by magnetic scanner in order to get uniform dose. The gate terminals of MOSFETs were biased at +2 V ($V_{GS}=+2$ V) during irradiation. The typical beam currents during irradiation were 1 and 0.125 pnA for 48 MeV Li^{3+} ions and 100 MeV F^{8+} ions respectively. The Co-60 gamma irradiation was done using gamma chamber with a dose rate of 167 rad/s at Pondicherry University in the dose range100 krad–100 Mrad. The total dose was kept identical for both high energy ions and gamma radiation.

The electrical characterization of the un-irradiated and irradiated MOSFETs were performed using computer interfaced 4155 HP Agilant Semiconductor Parameter Analyzer. The current resolution with the test setup was of the order of 1–100 fA. The threshold voltage (V_{TH}) and transconductance (g_m) was determined from the I_D versus V_{GS} characteristics. Among the several methods to measure the V_{TH}, one method is to choose a current level and define the V_{GS} required to produce that I_D as the V_{TH}. For example, V_{TH} equals the V_{GS} required to produce 1 μA of I_D, the total dose response determined using this method was qualitatively the same as the other methods like extrapolating the square-root of I_{DS} versus V_{GS} curve to $I_{DS}=0$ [22]. The mobility (μ) of carriers in the channel was determined by g_m measurements (at constant $V_{DS}=0.1$ V). While measuring the electrical parameters of the MOSFET, same voltage was applied to both the gates.

Table 1
The energy loss and range of 48 MeV Li3⁺ ion, 100 MeV F8⁺ ion and Co-60 Gamma radiation in metal oxide semiconductor (MOS) structure.

Source	LET in MeVcm²/g			Range in μm		
	Al	Si	SiO_2	Al	Si	SiO_2
48 MeV Li^{3+} ions	412.2	421.6	454.7	254.1	289.5	266.0
100 MeV F^{8+} ions	9307	4427	4723	63.65	72.65	68.05
Co-60 Gamma	1.544	1.600	1.651	1072	1206	1171

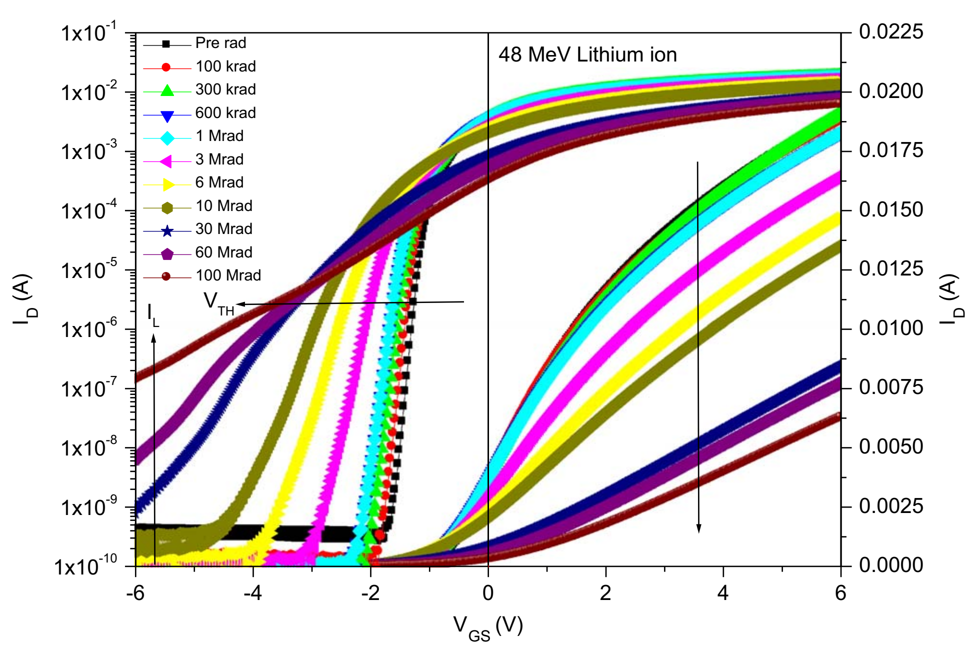

Fig. 1. Transfer characteristics of 48 MeV Li^{3+} ion irradiated MOSFET.