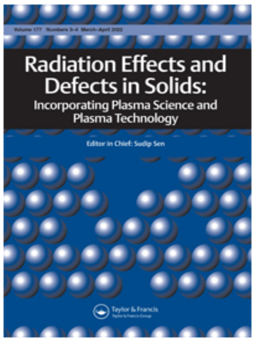

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The influence of radiation on the electrical characteristics of MOSFET and its revival by different annealing techniques

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ABSTRACT

Defects originate in N-channel MOSFETs by exposing them to high-energy ions and ^{60}Co gamma radiation separately to different radiation doses. The electrical variations in MOSFETs are characterized systematically before and after the influence of radiation on MOSFETs. The impact of ^{60}Co gamma radiation on threshold voltage (V_{TH}) and mobility (μ) characteristics of MOSFETs is more than the impact of high energy ions on MOSFETs. The annealing of electrical characteristics in the irradiated MOSFETs is studied systematically by isothermal and isochronal annealing techniques. The isochronal annealing technique is more preferable due to its high recovery rate than the isothermal annealing technique.

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KEYWORDS
MOSFET; radiation impact; threshold voltage; mobility

1. Introduction

Metal oxide semiconductor field-effect transistors (MOSFETs) are one of the building blocks in the integrated circuit (IC) industry and used in diverse radiation environments: space, high energy labs, radiotherapy clinics, for example (*1*). Low-energy particles from space and high-energy particles from the Large Hadron Collider (LHC) that interact in MOS devices can cause functional damage (*2, 3*). High-energy ions create ionization and displacement damage, whereas ^{60}Co gamma radiation produces point defects and collision cascades in addition to ionization in the MOSFETs. The damage created in MOSFET by ionization and displacement results from the production of oxide trapped charges in the gate oxide (SiO_2) and interface trapped charges at the silicon–silicon dioxide ($Si\text{-}SiO_2$) interface. These oxide and interface trapped charges may cause malfunctioning of electrical properties, such as threshold voltage (V_{TH}) and mobility of MOSFETs. For the use of MOS devices in space, the devices need to resist up to a few hundreds of gray (Gy) of gamma radiation dose, and for high-energy physics experiments like in LHCs, the MOS devices need to resist up to 1 MeV equivalent 10^{16} cm^{-2} fluences of neutron over years of life which is equal to few thousands of Gy of gamma equivalent total dose. The required time to reach such high doses is explicitly high with the present ^{60}Co gamma, electron and proton facilities. The required time to reach the same ^{60}Co gamma equivalent dose using high-energy ions is

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quite minimal to impact the MOSFETs. In recent times, some experiments have been conducted to understand the effect of high-energy ions on the bipolar junction transistors (BJTs) (3, 4), SiGe heterojunction bipolar transistors (HBTs) (5, 6) and N-Channel Depletion MOSFETs (7–9). The studies related to the impact of radiation on MOSFETs and their revival by different annealing techniques are very few (4, 7). Thus, the present work investigates the impact of different Linear Energy Transfer (LET) high-energy ions on threshold voltage (V_{TH}) and mobility of MOSFETs and recovery of its electrical characteristics, using different annealing techniques, to correlate the results with the ^{60}Co gamma impacts on MOSFETs.

2. Materials and methods

The MOSFETs chosen in this experiment are BEL (Bharath Electronics Ltd., India) made 3N187 of two serially connected N-channels with independent dual gates (2, 7). The identical characterized MOSFETs were chosen to experiment with the influence of radiation on the electrical characteristics of MOSFETs. Different sets of MOSFETs were chosen for different high-energy ions and ^{60}Co gamma irradiation. The different high-energy ions, such as 50 MeV Lithium ions, 95 MeV Oxygen ions, 100 MeV Fluorine ions, 140 MeV Silicon ions, 175 MeV Nickel ions and ^{60}Co gamma radiation, were chosen to analyze their impacts on the electrical characteristics of the MOSFETs. The 15 UD 16 MV Pelletron Accelerator facilities at Inter University Accelerator Center (IUAC), New Delhi, India are used to create different high-energy ion impacts on MOSFETs by irradiation process. The experiments were performed at 300 K temperature and 10^{-7} torr pressure with the ion fluence range from 2×10^8 to -1.53×10^{13} ions/cm^2. The comparable ^{60}Co gamma radiation dose for this fluence was from 1 kGy to 1 MGy. The ion beam scanned the device over an area of 1 cm by 1 cm. The typical ion beam current 1 p-nA (one particle nanoampere) for 50 MeV Lithium ions, 0.29 p-nA for 95 MeV Oxygen ions, 0.125 p-nA for 100 MeV Fluorine ions, 0.1 p-nA for 140 MeV Silicon ions and 0.03 p-nA for 175 MeV Nickel ions were maintained throughout the experiment. The gate terminals of the MOSFETs were biased at 2.0 V. The ^{60}Co gamma radiation impact on MOSFETs was measured at Pondicherry University, Puducherry using gamma chamber 5000 with a dose rate of 1.67 Gy per second. SRIM-2011 simulation program (10) analyzed the energy loss and range of different ions in the MOSFETs. The Keithley 2636A Semiconductor Parameter Analyzer was used to characterize the MOSFETs before and after experimenting. The V_{TH} was extracted from the $I_D x V_{GS}$ transfer characteristic curve of the MOSFET. ΔN_{it} and ΔN_{ot} were projected using the subthreshold measurements (11, 12). The mobility (μ) of carriers in the channel was determined from transconductance measurements of the MOESFETs. The recoveries in the electrical characteristics of irradiated MOSFETs were studied by isothermal and isochronal annealing techniques using high-temperature ovens and furnaces. The MOSFETs exposed up to 1 MGy of total dose were subjected to isothermal annealing at 200°C for the different time period up to 100 h and allowed for natural cooling to study the annihilation of the defects in the irradiated MOSFETs. The MOSFETs exposed up to 1 MGy of total dose were subjected to isochronal annealing from 50°C to 400°C at 1 h duration for each temperature and allowed for natural cooling to measure V_{TH} and μ parameters of the MOSFET.

3. Results and discussion

The identical characterized MOSFETs were separately exposed to different high-energy ions and ^{60}Co gamma radiation under identical experimental conditions to induce radiation impact on the MOSFETs. The time required for different LET high energy ions and ^{60}Co gamma to reach the same radiation dose is listed in Table 1. From Table 1 it is clear that to give 1 MGy of radiation dose need around 167 h time using ^{60}Co gamma source, on the other hand, the same radiation dose can be given in around 55 min using 50 MeV Lithium ions, 18 min using 95 MeV Oxygen ions, 30 min using 100 MeV Fluorine ions, 18 min using 140 MeV Silicon ions and 18 min using 175 MeV Nickel high energy ions, respectively. When high-energy ions travel through a solid material, they lose energy by electronic excitations called electronic energy loss, $<dE/dx>e$ (S_e) and direct nuclear collisions with the target material called nuclear energy loss, $<dE/dx>n$ (S_n). The SRIM-2011 simulation program was used to calculate the energy loss and range of different high energy ions in the MOSFETs, and the details are given in Table 2. From Table 2, it can be observed that for a given energy of different ions, the electronic energy loss is quite high compared to nuclear energy loss. The energy deposited in the MOSFET is mainly due to electronic energy loss. The nuclear energy loss is high near the end of the ion range, including point defects and collision cascades. Using SRIM simulations one can estimate the passage of the different ions through the active region of the MOSFETs.

The variation in V_{TH} with total radiation dose and annealing time for ^{60}Co gamma and different high energy ion impact on MOSFETs are shown in Figure 1. To understand the recovery in the electrical characteristics of ion impact MOSFETs, it is important to know the high-temperature annealing studies in irradiated devices. Annealing defects can occur when a vacancy and an interstitial atom combine. It is well known that the radiation-induced oxide and interface trapped charges degrade the current–voltage characteristics ($I \times V$) of the MOSFET. In the present work the different electrical parameters, such as threshold voltage (V_{TH}) and mobility (μ), are studied after isothermal and isochronal annealing.

To create radiation impact on MOSFETs the devices were irradiated up to 1 MGy of total radiation dose and were subjected to isothermal annealing for different periods up to 100 h at a constant temperature of 200°C. Then, natural cooling was performed to study the annealing effects. It can be seen that a significant recovery in V_{TH} was observed after annealing. The V_{TH} values for different radiation impacts and annealed MOSFETs are listed in Table 3. From Table 3 it can be observed around 70–100% recovery in the V_{TH} after annealing up to 100 h.

In the isochronal annealing technique, the MOSFETs exposed up to 1 MGy of total radiation dose were subjected for annealing from 50°C to 400°C in different steps for 1 h. The annealed devices were allowed for cooling up to room temperature. The important electrical parameters were studied after annealing. The recovery in V_{TH} with annealing temperature for radiation impact MOSFETs is shown in Figure 2, and the readings are recorded in Table 4. It is evident from this figure that V_{TH} increases with an increase in temperature, and the annealing rate is higher in the temperature range between 150°C and 250°C. It can be observed from Table 4 that the V_{TH} recovers almost 100% after annealing at 300°C. Figure 1 shows the variation in V_{TH} with total dose and annealing time. It can be observed that from Figure 1 and Table 1, after 100 kGy of ^{60}Co gamma dose, the V_{TH} is decreased by

Table 1. The required time for different high-energy ions and ^{60}Co gamma to reach respective radiation dose.

	Required time to reach respective radiation dose									
Radiation source	1 kGy	3 kGy	6 kGy	10 kGy	30 kGy	60 kGy	100 kGy	300 kGy	600 kGy	1 MGy
^{60}Co gamma	10 min	30 min	60 min	1 h 40 min	5 h	10 h	16 h 40 min	50 h	100 h	166 h 40 min
50 MeV Lithium ions	3 s	10 s	20 s	33 s	99 s	3 min 17 s	5 min 29 s	16 min 30 s	32 min 50 s	54 min 59 s
95 MeV Oxygen ions	1 s	3 s	7 s	11 s	33s	1 min 6 s	1 min 50 s	5 min 25 s	10 min 50 s	18 min 5 s
100 MeV Fluorine ions	2 s	6 s	11 s	18 s	54s	1 min 48 s	3 min	9 min 1 s	18 min 3 s	30 min 4 s
140 MeV Silicon ions	1 s	3 s	7 s	11 s	33 s	66 s	1 min 50 s	5 min 30 s	11 min	18 min 20 s
175 MeV Nickel ions	1 s	3 s	6 s	11 s	32 s	64 s	1 min 47 s	5 min 20 s	10 min 40 s	17 min 47 s

Table 2. Electronic energy loss, nuclear energy loss and range of ions in MOSFETs.

		Se (keV/μm)			Sn (keV/μm)			Range in μm		
Radiation Source	Energy (MeV)	Al	Si	SiO_2	Al	Si	SiO_2	Al	Si	SiO_2
Li^{3+} ions	50	111.4	97.86	105.5	0.06	0.055	0.06	254	289.5	266
O^{7+} ions	95	851.3	747.5	800	0.46	0.47	0.43	77.5	88.4	83
F^{8+} ions	100	1171	1027	1096	0.65	0.59	0.60	63.7	72.7	68
Si^{10+} ions	140	2409	2114	2251	1.58	1.45	1.48	46.5	53	50
Ni^{13+} ions	175	8091	7077	7487	9.23	8.4	8.58	27	30.6	28.6
^{60}Co gamma	$\sim$ 1 MeV electron	1.54	1.6	1.65				–	–	–

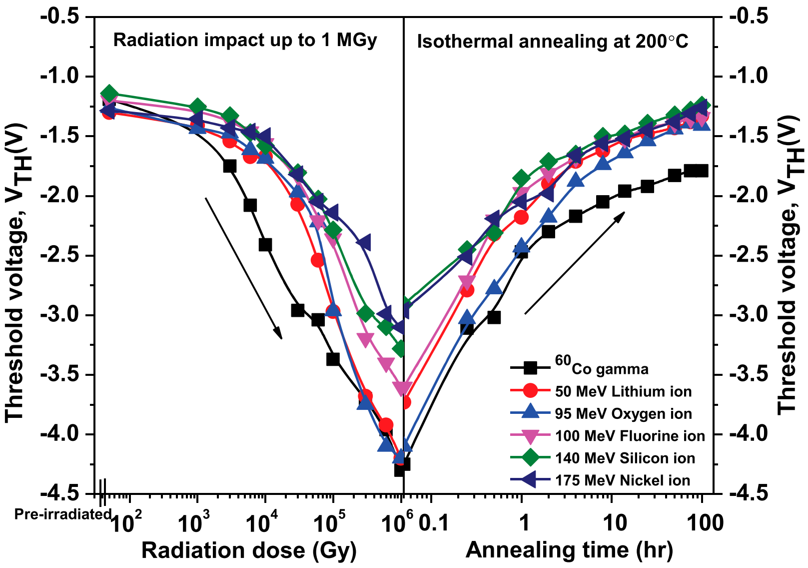

Figure 1. The threshold voltage as a function of radiation dose and annealing time after ^{60}Co gamma and different ions impact on MOSFET.

Table 3. The change in V_{TH} before and after the impact of radiation on MOSFET and after isothermal annealing.

	V_{TH} (V)			
Radiation source	Before irradiation	After 1 MGy radiation dose	Annealing at 200°C for 100 hrs	% Recovery in V_{TH} (V)
^{60}Co gamma	−1.32	−4.6	−1.79	73.7
50 MeV Li ions	−1.32	−3.73	−1.33	99.25
95 MeV O ions	−1.32	−3.18	−1.41	93.6
100 MeV F ions	−1.32	−3.0	−1.34	98.5
140 MeV Si ions	−1.32	−2.91	−1.24	100
175 MeV Ni ions	−1.32	−2.96	−1.26	100

−2.2 V and irradiation time is around 17 h. But in the case of 1 MGy of ^{60}CO gamma dose, the decrease in V_{TH} is only −3.3 V, whereas the irradiation time is 167 h. It reveals that during the gamma irradiation for a longer time, in addition, to reducing in $V_{TH,}$ the annealing

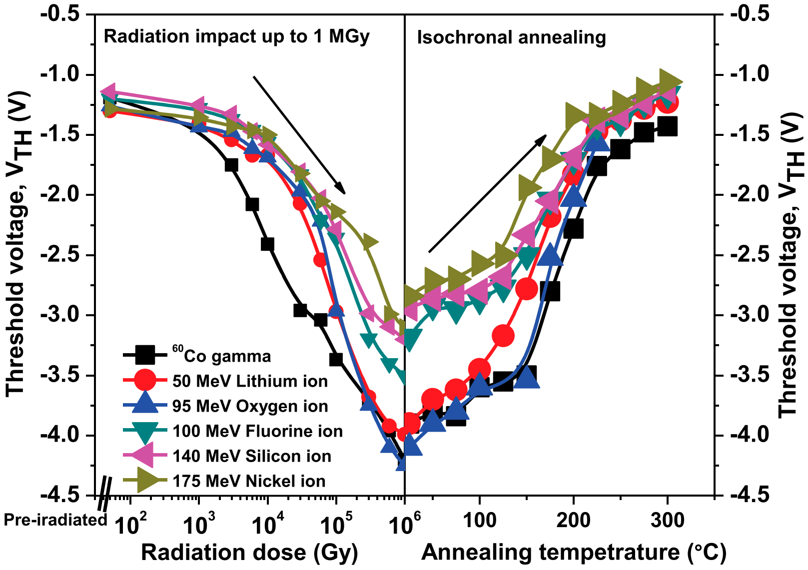

Figure 2. The threshold voltage as a function of radiation dose and elevated temperature after ^{60}Co gamma and different ions impact on MOSFET.

Table 4. The change in V_{TH} before and after the impact of radiation on MOSFET and after isochronal annealing.

Radiation source	Total dose	V_{TH} (V) Before irradiation	 After 1 MGy radiation dose	 After annealing up to 300°C	% recovery in V_{TH} (V)
^{60}Co gamma	1 MGy	−1.32	−4.2	−1.31	100
50 MeV Li ions	1 MGy	−1.32	−3.99	−1.23	100
95 MeV O ions	1 MGy	−1.32	−4.25	−1.41	94
100 MeV F ions	1 MGy	−1.32	−3.5	−1.16	100
140 MeV Si ions	1 MGy	−1.32	−3.2	−1.13	100
175 MeV Ni ions	1 MGy	−1.32	−3.1	−1.06	100

of the trapped charges also takes place. As a result, the rate of decrease in V_{TH} was reduced at higher total doses.

The mobility of carriers in the MOSFETs was calculated using the formula $\mu_{FE} = \frac{Lg_m}{ZC_{OX}V_{DS}}$, when this expression is solved then μ is μ_{FE} where μ_{FE} is the field-effect mobility, g_m is the peak transconductance (7), L is the length, Z is the width and C_{OX} is the oxide capacitance per unit area of the MOSFET (2, 7). The reduction in normalized μ with an increase in radiation dose and the recovery in the normalized μ with annealing time for different ions and ^{60}Co gamma impact MOSFETs are shown in Figure 3. From Figure 3, it can be seen that the normalized μ is found to decrease with an increase in radiation dose and observed to recover around 50% under isothermal annealing. The variation in normalized μ with an increase in radiation dose and the recovery in the normalized μ with an increase in temperature for different ions and ^{60}Co gamma impact MOSFETs are shown in Figure 4. From Figure 4 it can be observed that normalized μ decreases with an increase in radiation dose. It can also be observed that up to 150°C there is not much recovery in normalized μ. Only after

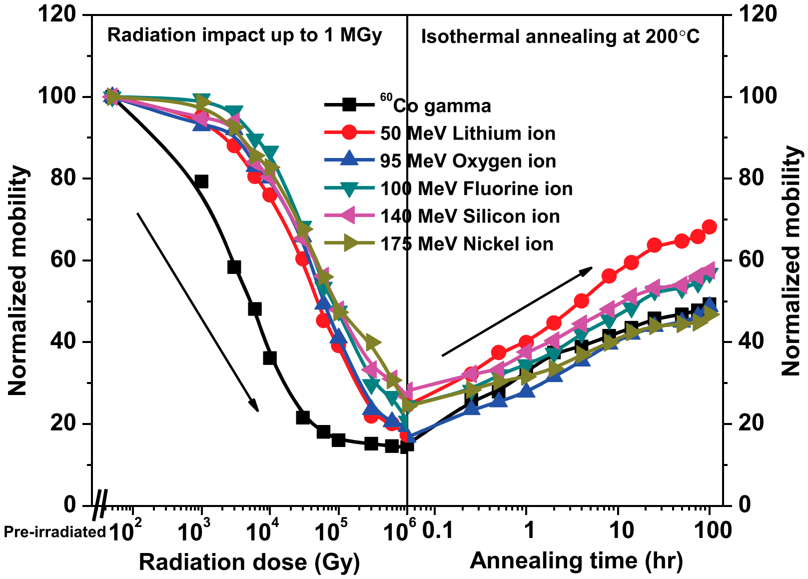

Figure 3. The normalized mobility as a function of radiation dose and annealing time after ^{60}Co gamma and different ions impact on MOSFET.

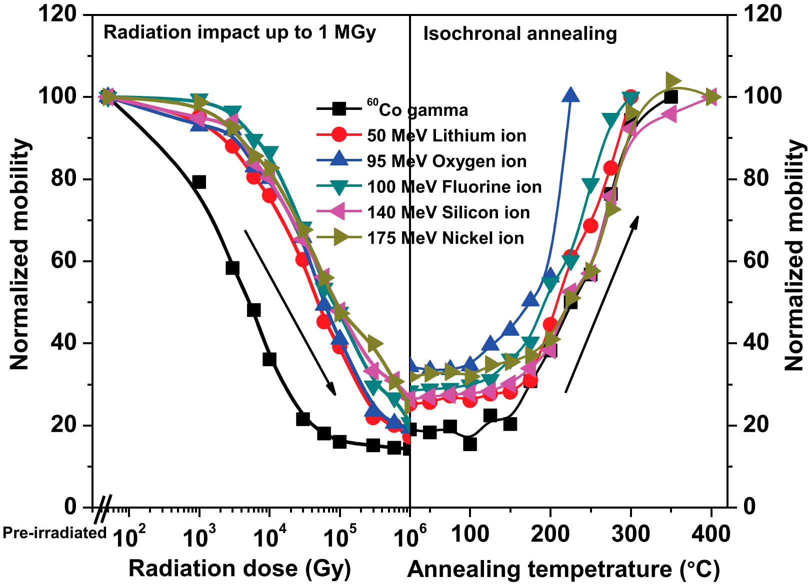

Figure 4. The normalized mobility as a function of radiation dose and elevated temperature after ^{60}Co gamma and different ions impact on MOSFET.

150°C there is a sharp recovery in normalized μ. It can be seen from the figure that almost 100% recovery in normalized μ after annealing at 300°C under the isochronal technique.

It can be observed from Figure 3 that for ^{60}Co gamma-irradiated MOSFETs the normalized μ sharply decreases up to 100 kGy of total dose and above 100 kGy of total dose, the normalized μ saturates until 1 MGy of total dose due to annealing of trapped charge. In isothermal annealing the irradiated MOSFETs were annealed at 200°C for 100 h, only about 70–100% recovery in V_{TH} and about 50–70% recovery in normalized μ took place. Whereas in the isochronal annealing technique V_{TH} and normalized μ are recovered at 300°C. This is due to radiation-induced oxide trapped charges and interface trapped charges in MOSFET being completely annealed after 250°C in this method. The experimental annealing results of revival in V_{TH} and normalized μ show that the isochronal annealing technique is preferable due to its high recovery rate compared to the isothermal annealing method.

4. Conclusion

The electrical parameters, such as threshold voltage (V_{TH}) and normalized mobility (μ), were studied before and after different high-energy ions and ^{60}Co gamma irradiation effects on the N-channel MOSFETs. V_{TH} and normalized μ were decreased after different high-energy ions and ^{60}Co gamma radiation impacts on MOSFETs. The impact of ^{60}Co gamma radiation is greater than some high-energy ions. This is because ^{60}Co gamma creates a more trapped charge in SiO_2 compared to different high-energy ions. The recovery in V_{TH} and normalized μ was studied systematically by isothermal and isochronal annealing techniques. The annealing results showed that the isochronal annealing technique was found to be preferable due to its high recovery rate compared to the isothermal annealing method.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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