Behavior of power MOSFETs during heavy ions irradiation performed after γ-rays exposure

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A B S T R A C T

The behavior of medium voltage commercial power MOSFETs, first degraded with increasing γ-rays doses and subsequently irradiated with heavy ions, is presented. It is shown that the degradation of the gate oxide caused by the γ-irradiation severely corrupt the SEE robustness and drastically modify the physical behavior of the device under test after the impact of a heavy ion. A decrease of the critical voltages at which destructive burnouts and gate ruptures appear has been detected in all devices previously irradiated with γ-rays. The amount of the critical voltage reduction is strictly related to the amount of the absorbed γ-rays dose. Furthermore, at the failure voltage, the behavior of the device is affected by the conduction of a current through the gate oxide. Moreover the SEGR of the device appears at lower voltages due to the reduction of the Fowler–Nordheim limit in the γ-irradiated devices.

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1. Introduction

Power MOSFET’s are very important electron devices in power converters and their safe use in harsh radiation environment, like aerospace missions or high energy nuclear physics experiments [1], is a goal to reach. When energetic photons or particles impinge on the device structure they lose energy by ionization or by collision causing defects and changes in the electrical behavior which can lead the device to a premature failure. Ionizing mechanisms include total ionizing dose (TID) and single event effect (SEE).

Although TID and SEE have been widely studied in the literature [2–11], not much work has been done so far to study the combined effects of the phenomena involved in TID and SEE. These combined effects may become particularly significant not only in space applications but also in high energy nuclear physics experiments where high energy neutron or proton, which does not produce enough charge to directly cause a SEE, can originate by spallation a recoil nucleus heavier than the original particle, able to generate a sufficient amount of electron-hole pairs to induce a SEE [12].

In this work the behavior of medium voltage commercial power MOSFETs, first degraded with increasing γ-rays doses and subsequently irradiated with heavy ions, is presented. Experimental results show that the surface changes caused by γ-irradiation severely corrupt the SEE robustness and drastically modify the physical behavior of the device under test after the impact of a heavy ion. A decrease of the critical voltages at which destructive

burnouts and gate ruptures appear has been detected in all devices previously irradiated with γ-rays, the amount of the critical voltage reduction is strictly related to the amount of the absorbed γ-rays dose.

2. Experimental results

The combined experiments were developed in two phases. In the first phase commercial power MOSFETs were irradiated at different total doses up to 10 kGy[SI] with the Calliope 60Co γ-rays source of the ENEA Casaccia Research Center, Rome, Italy. In the second phase, the same samples were irradiated with high energy bromine ions able to stimulate failure mechanisms in the MOSFET structure. The heavy ion irradiation was performed at the Laboratori Nazionali del Sud, INFN, Catania, Italy.

The tested devices belong to a commercial 200 V n-channel power MOSFETs family.

2.1. γ-Irradiation

In the first phase the samples were irradiated with four different γ-doses: 1.60, 3.20, 5.89 and 9.60 kGy[SI] with a dose rate of 10 Gy/h (about 0.28 rad/s). The highest dose was chosen in order to comply with the specification of the ATLAS experiment [1]. For each dose at least three different samples were tested. During the γ-irradiation the drain and the source of the tested device was grounded and $V_{GS}$ was set to the 80% of the maximum nominal gate voltage. After the irradiation all the samples were annealed for about 1 week at a temperature of 100 °C. For each device, the shifts of threshold voltage and breakdown voltage, on-resistance and...
oxide current leakage were measured at the given measurement points. The results are displayed in Figs. 1–4, at doses increasing up to 9.60 kGy.

Our results confirm what is normally observed on power MOSFETs after $\gamma$-irradiation: ionization damage affects the SiO$_2$ oxide of the MOS structure causing the build-up of trapped charge, a growth of the amount of interface traps and an increase in the number of bulk oxide traps [2–7]. Ionization creates electron-hole pairs in the dioxide; electrons quickly move under the electric field influence to the contacts, on the other hand, the holes, having a very low effective mobility, may be trapped in the oxide. Some holes slowly diffuse near the Si–SiO$_2$ interface where they will accumulate and will capture electrons and create interface defects which work as traps for electrical charges depending on the polarity of the applied gate bias. The fixed charges trapped in the oxide alter the promptness of the inversion layer build-up modifying the threshold voltage. The monotonic decrease in the threshold voltage reported in Fig. 1 denotes a positive net trapped charge. The slope variation of sub-threshold current indicates also the trapping of charges at oxide–silicon interface [8].

The reduction of the breakdown voltage, observed in Fig. 2 at increasing doses, is consistent with the mechanism described in [5] which attributes to the positive charges trapped in the field oxide the modification of the surface potential at the body-drain junction termination and the consequent reduction of the curvature radius of the depletion region.

In Fig. 3, we show the mean value of the on-resistance measured on each group of samples as a function of the dose each group had absorbed. The figure shows no significant changes in the resistance values, indeed, TID degrades the carriers surface mobility and causes the increase of the channel resistance which is a small amount of the total on-resistance in our devices. Instead, the main component of the on-resistance, which is due to the bulk region, is not affected by TID. In fact, at the maximum dose of 9.60 KcGy(SI) used in our experiments, the amount of displacement damages induced by $\gamma$-irradiation, which cause the reduction of the carriers mobility in the bulk region, can be neglected as compared to the surface changes [13].

Finally, in Fig. 4, the overlap of the leakage gate currents recorded on each group of samples as a function of the dose each group had absorbed. The figure shows no significant changes in the resistance values, indeed, TID degrades the carriers surface mobility and causes the increase of the channel resistance which is a small amount of the total on-resistance in our devices. Instead, the main component of the on-resistance, which is due to the bulk region, is not affected by TID. In fact, at the maximum dose of 9.60 KcGy(SI) used in our experiments, the amount of displacement damages induced by $\gamma$-irradiation, which cause the reduction of the carriers mobility in the bulk region, can be neglected as compared to the surface changes [13].

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device (squares label) and for a 3.20 kGy γ-irradiated device (circles label) at $V_{DS} = 40$ V. The comparison shows a significant conduction mechanism, for the γ-irradiated device, at a voltage value lower than the knee of the Fowler–Nordheim characteristic. This conduction mechanism is not observed at $V_{DS} = 0$ V, as displayed in Fig. 4.

2.2. Heavy ions irradiation

In the second experimental phase, both fresh and γ-irradiated devices were exposed to a beam of $^{79}$Br ions at 155 MeV. The charge generated in the device as a consequence of an ion impact is partly collected at the external leads where it produces a current pulse that is recorded by a fast sampling oscilloscope; the drain current waveforms are acquired and the related charges are numerically computed. A statistical procedure, allows us to obtain a compact information regarding the acquired data in terms of their mean and variance. A detailed description of the heavy ion experimental set-up is reported in [11].

During each irradiation the device under test is biased at constant $V_{DS}$ and $V_{GS}$. For γ-irradiated devices, $V_{GS}$ was set to a negative value for compensating the effects of the threshold shift. We used the minimum $V_{GS}$, in absolute value, able to guarantee normally off operation of the DUT; the corresponding values are shown in the second column of Table 1. For each device, several tests were repeated at increasing $V_{DS}$ until a single event failure had been detected. The $V_{DS}$ at which damages or failures were observed are reported in the third column of Table 1.

All the not γ-irradiated devices experienced a SEB at $V_{DS}$ between 100 V and 110 V. The SEB nature of the failure is confirmed by the registration during the irradiation of a single very large current pulse like the one indicated by the large curve of Fig. 6. In this case the SEB pulse was clipped in order to protect the instrumentation. In the figure the typical pulses (smaller curves) normally recorded in the same bias condition are also displayed for comparison and zoomed in the inset.

Table 1 shows that the increase of the dose, previously absorbed by DUT during γ-irradiation, causes a reduction of the single event failure voltage which goes down to 40–45 V for the 9.60 kGy dose.

For the not γ-irradiated devices, no drain current pulse having very high peak was registered during the irradiation. Moreover, large increases of both the drain and gate leakage currents measured after the failure indicates serious damages both at drain and gate sides of the DUTs thus making difficult to distinguish whether the failures were associated to a SEB or a SEGR.

Let us first consider the behavior of the γ-irradiated devices observed during the heavy ions exposures at $V_{DS}$ lower than the SE critical voltage. This behavior is very similar to the one of the not γ-irradiated samples. The scatter plots of the collected charge vs. the current peaks associated to 1500 events registered during Br irradiation, at $V_{DS} = 35$ V, are depicted in Fig. 7 for a fresh device (a), and a 9.60 kGy γ-irradiated sample (b). The two scatter plots are almost identical to one another and to those ones measured after 3.20 and 5.89 kGy irradiation, not shown for brevity.

Moreover the amount of collected charge during the Br ions impacts is weakly dependent on the absorbed dose as indicated...
in Fig. 8 where the mean values of the collected charge are displayed as a function of the \( V_{DS} \) applied during the irradiation. In the figure, we report five groups of points each referring to a single device exposed at a different \( \gamma \)-rays dose. Each point of each group corresponds to a different value of \( V_{DS} \) applied on the device during the heavy ion irradiation and indicates the mean value of the collected charge measured on a population of about 1500 current pulses recorded during the \( B_r \) irradiation. The figure shows that TID induces no substantial changes in the charge collected during \( B_r \) impacts. 3-D finite element SEE simulations, not shown here for brevity, have confirmed that TID doesn’t appreciably alter the current waveform and, then, the relative charge.

This result, together with the invariance of the \( R_{on} \), indicates that the silicon part of the device (source, body, drain, parasitic BJT, etc.) is weakly affected by the \( \gamma \)-irradiation.

Let us now consider the behavior of the device at the biasing conditions where failures occur. For the 1.60 kGy \( \gamma \)-irradiated device, the scatter plot measured at the critical voltage, \( V_{DS} = 70 \) V, not shown here for brevity, is very similar to that one of the fresh device even if the sample under test exhibited a Single Event Burnout.

Instead, for the other devices, the behavior becomes much different as depicted in Fig. 9 where the scatter plots, at \( V_{DS} = 40 \) V, are depicted for a fresh device (a), 3.20 (b), 5.89 (c) and 9.60 (d) kGy \( \gamma \)-irradiated samples. After the \( B_r \) irradiations, at the test conditions of Fig. 9, the fresh device survived whilst the other samples failed.

The scatter plot of Fig. 9a, related to a fresh device, shows a single population of events as already noticed in Fig. 7a. The shapes of the typical current pulses are depicted by the two insets of the figure. Both of them have a rapid rise and a slower fall down. The pulse with the larger peak (the light blue\(^1\) curve on the right side of the plot) has a current descent faster than that one of the pulse with the smaller peak (the dark blue curve on the left-high side of the plot). The scatter plots of Fig. 9b–d show a second population of events. This second population is very large and reduces the population already observed on the fresh device which is made of pulses with large current peak and fast descent (the light blue curves evidenced in each scatter plot). The second population concentrates in the low-left side of the scatter plot so that it is made of pulses with small peaks and collected charge larger than that one collected for the first population.

For the reader convenience, the typical current pulses of the first and the second populations are once more reported in Fig. 10a and b, respectively. We can observe that the pulse (b), although has a similar peak to the pulse (a), exhibits a current tail which slows down the descent of the current to zero and causes the increase of the collected charge. It is worth noting that in many cases the tail is longer than the time-base of the oscilloscope so that the collected charge results sometimes underestimated.

In each of Fig. 9c and d a red current curve is also displayed. We attribute these curves to the single events that have caused the devices destruction. They are characterized by a relatively small value of the current which remains practically constant after the impact, we attribute these failures to SEGRs. It worth noting that the peak of these current pulses is much lower than that one observed during the SEB of the not \( \gamma \)-irradiated devices, see Fig. 6.

3. Discussion

Experimental results have shown that at voltages lower than the SE failure voltage, the \( \gamma \)-rays degradation does not alter the current pulses shape and the related generated charge. However, for doses larger than 1.60 kGy, at the SE critical voltage, we can observe that:

\(^1\) For interpretation of color in Figs. 1–3, 5–11, the reader is referred to the web version of this article.
The equivalent circuit of a MOSFET cell is schematized in Fig. 11 together with the parasitic elements of its structure.

- The drain current measured at the SEGR is much smaller than the SEB drain current on not γ-irradiated devices.
- The population with small peak current pulses becomes much larger than the corresponding one in not γ-irradiated devices.
- A tail appears in the drain current pulses.

In order to give a possible interpretation of these phenomena, the equivalent circuit of a MOSFET cell is schematized in Fig. 11 together with the parasitic elements of its structure. We propose here that, for the high doses γ-irradiated devices at the critical SE conditions, the gate oxide is involved in the activation of the parasitic bipolar transistor contrarily to what happens in not γ-irradiated devices and in the γ-degraded ones at lower $V_{DS}$.

In fact, after an ion impact, a large electric field is applied across the gate oxide and at the right edge of the P+-body causing a current pulse related to the first population of events (a) and to the second population of events (b).

![Image 10](image10.png)

**Fig. 10.** A current pulse related to the first population of events (a) and to the second population of events (b).

![Image 11](image11.png)

**Fig. 11.** Elementary cell of a power MOSFET with the equivalent circuit including the parasitic elements of the structure.

rent to flow through $R_{B1}$ and $R_{B2}$. This current can forward bias the emitter of the parasitic bipolar transistor inducing a collector current measured at the external leads [11]. In high doses γ-irradiated devices the electric field across the degraded oxide induces a current through it reducing the amount of current flowing through the P+-body. Consequently, the peaks of the collector current are reduced in comparison to a not γ-irradiated device.

Moreover, the capacitance $C_{GB}$ is charged during the time when the electric field is applied across the oxide and then is discharged through $R_{B1}$, $R_{B2}$ and the degraded gate oxide. This discharge prolongs the current flow through the base and sustains the tail in the drain current pulses as evidenced in Fig. 10b.

It is worth noting that the amount of the collected charge in high doses γ-irradiated devices is not much different than in not γ-irradiated devices. In fact the reduction of the peaks in the current pulses is compensated by the increase of their tails.

Finally, we attribute the failure of the γ-degraded devices to SEGR. In fact a SEGR takes place when a heavy ion impacts on a sensitive volume of the device under test where it induces across the oxide a voltage larger than the Fowler–Nordheim limit. In high doses γ-irradiated devices this limit is significantly reduced as indicated in Fig. 5 so that these devices show a gate rupture at $V_{GS} = −6$ V and $V_{DS} = 40$ V–50 V. It is worth noting that for the fresh devices SEGR takes place at $V_{GS} = −10$ V and $V_{DS} = 40$ V–50 V.

4. Conclusions

The behavior of commercial power MOSFETs, first degraded with increasing γ-rays doses and subsequently irradiated with heavy ions, is presented. Experimental results show that the changes at the gate oxide caused by γ-irradiation severely corrupt the SEE robustness and drastically modify the physical behavior of the device under test. The degraded gate oxide plays a role in the activation of the parasitic bipolar transistor inherent the MOSFET structure and causes the reduction of the collector current peak. The shape of the current pulses measured at the external leads is modified by the conduction through the degraded oxide.

The failure mechanism can be attributed to a SEGR which takes place at lower gate and drain voltages due to a conduction mechanism caused by the γ-irradiation.

References