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Experimental study about gate oxide damages in patterned MOS capacitor irradiated with heavy ions

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ABSTRACT

In this paper we present the results of an experimental work aimed to study the formation of "gate oxide damages" in patterned MOS capacitors during heavy ion irradiation. The samples under test are derived from 100 V power MOSFETs. The damages on these structures have the same nature of the corresponding MOSFET but can be much more easily characterized. The gate damages resulting from both ^{79}Br and ^{197}Au ion irradiations are presented for different test conditions.

1. Introduction

Many papers dedicated to Single Event Gate Rupture (SEGR) of power MOSFETs report experimental evidence of such a phenomenon [1,2] and correlate it to characteristics of the penetrating ions (LET, range, energy, angle, etc.) [3–7] to the technological characteristics of the samples (cellular or stripe structures, oxide thickness, cell pitch, etc.) [8–15] and to its biasing conditions (gate and drain voltage, temperature, etc.) [16–19].

Besides SEGR, other radiation induced damages at the gate oxide are reported in the literature. In particular a radiation induced leakage current (RILC) in thin and ultra thin oxides is observed after heavy ion irradiation [20–23]. Moreover, radiation induced soft breakdowns (RSB) are also observed in these oxides [24–29]. It was demonstrated that heavy ion strikes on floating MOSFETs produce only modest changes in the devices' electrical characteristics that can be attributed to the presence of "latent damages" left by the heavy ion strikes in the gate oxide. The formation of "latent damages" has also been observed in power MOSFETs [30], which have much thicker gate oxide.

For these devices the term "latent damages" was used in the literature because they do not show up during the irradiation when the gate leakage current exhibits only a small increase. But if the device is under posed to a Post Irradiation Gate Stress the leakage current at the gate terminal increases significantly and the gate oxide becomes irreparably damaged. To put in evidence these latent damages a two phase experiment is suggested both by the literature [30] and by the reference standard MIL-STD/750 method 1080. This technique may take a long time to be performed and may cause the destruction of the sample under test. Moreover, the characteristics of the power MOSFET result to be only lightly affected by low fluence irradiation [30]. Because of that, instead of using power MOSFET, we performed the experiment on a set of specifically constructed patterned MOS capacitors. These devices were constructed with the standard process for a 100 V planar power MOSFET in which the n+ source diffusion was not performed. In such a way we neutralized the effect of the parasitic bipolar transistor. Moreover, we can consider these capacitors as gate–drain capacitors sideways bordered by the body diffusions, with a transverse electric field modulated by the same body diffusion when properly contacted.

The aim of this paper is to present the results of an experimental work aimed to investigate the formation of gate damages on these patterned capacitors as a consequence of a heavy ion irradiation. These damages are evidenced by the reduction of the Fowler–Nordheim conduction threshold whose amount is correlated to the entity of the damage created. This amount is proportional to the biasing voltage applied during the irradiation, the fluence and the energy of the impacting ions used in the irradiation.

2. The experimental procedure

The devices were irradiated at the Laboratori Nazionali del Sud-INFN (Catania) with ^{79}Br ions accelerated at 223 MeV and with ^{197}Au ions accelerated at 246 MeV. The Bragg diagram of these two species are reported in Fig. 1.

The devices were IV characterized with a parameter analyser before the irradiation, then they were exposed to the ion beam and after the irradiation they were again characterized in order to detect possible damages.

In Fig. 2, the sketch of half elementary cell of the patterned capacitors is reported together with the schematic of the biasing connections used for pre- and after-irradiation IV characterization.

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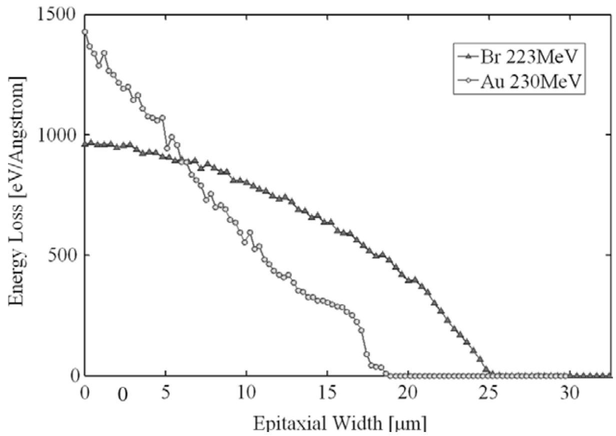

Fig. 1. The Bragg diagram of heavy ions used for the irradiation.

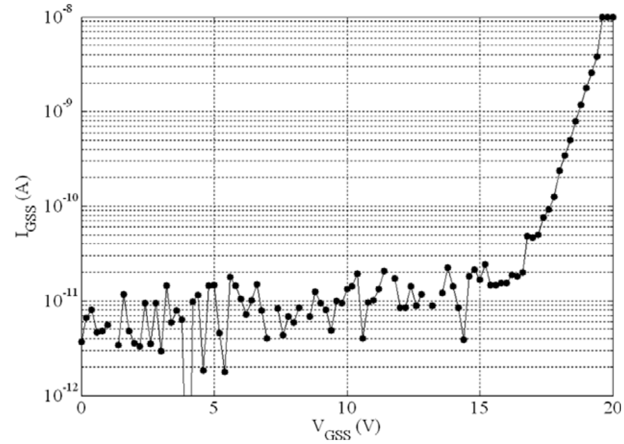

Fig. 3. The I_{GSS} characteristic on a fresh device.

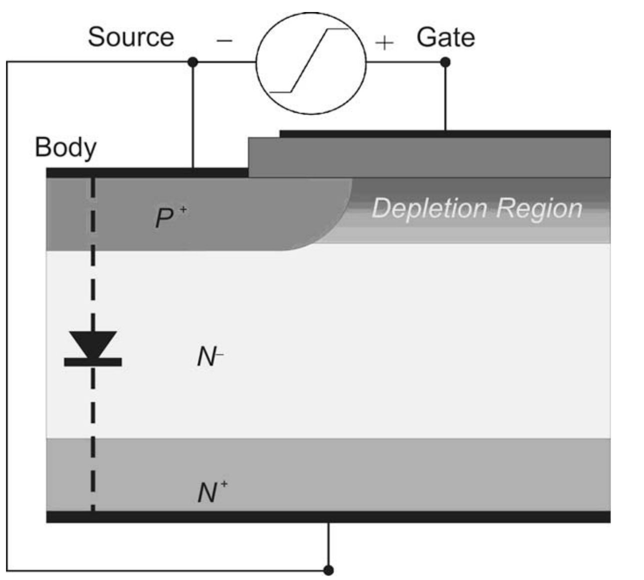

Fig. 2. The sketch of half elementary cell of the patterned capacitors inserted in the schematic of the biasing connections used for pre- and after-irradiation IV characterization.

The I_{GSS} is measured when the device is biased at a increasing positive V_{GSS}, when the body terminal is shorted to the source terminal.

In Fig. 3, the typical pre-irradiation I_{GSS} characteristic is reported. It was measured on a fresh device and reveals that the Fowler–Nordheim conduction knee for the I_{GSS} is at about 18 V on a fresh device.

During irradiation the devices were exposed to a very small ion flux (∼1–3 ion/s) with a variable number of impacting ions. The devices were biased at $V_{GS} = -2$ V and at a positive V_{DS} voltage, in order to reverse bias the epi/gate diode junction just below the gate capacitor interface.

This choice allows us to obtain a higher electric field in the depletion region underneath the gate oxide and to collect the maximum amount of generated charge during the ion strike. It is worth outlining that the gate/drain capacitor is here reverse biased, so that a depletion region and an inversion condition are present in the low-lying silicon. As a consequence, the applied drain/gate voltage is shared between the gate oxide and the same space charge region in the underlying drain interface, with a large fraction of the total electric field within the semiconductor.

The schematic of the experimental circuit used during the irradiation is reported in Fig. 4.

The charge generated during an ion impact produces a current transient that is detected by a fast deep memory data logger (a four trace sampling oscilloscope with four G samples/s and a 1 GHz band width). The time scale of the current pulse is of the order of a few nanoseconds hence the circuitry was adapted to the impedance of the cables (50 Ω).

The DUTs were "kept in off state" during irradiations at varying gate and drain biases (V_{GS} less or equal to 0 V, V_{DS} positive). During the exposure, drain and gate leakage currents are monitored in order to identify the values of V_{DS} and V_{GS} at which the gate and/or the drain structures become damaged; moreover, the current waveforms related to each ion impact are acquired and the related collected charges are numerically computed as the time integrals of the current. The total number of current pulses acquired by the oscilloscope is also used to determine the exact number of ions impacting on the device active area.

A high resolution parameter analyser (Agilent B1500 A) is used both to force the desired V_{GS} biasing voltage at the gate lead and to measure, in real time during the irradiation, the evolution of the gate leakage current I_{GSS} with a very high resolution. The better time resolution of the parameter analyser, as it is used in our experiments, is 1 ms hence the stray parameters of the cables does not affect the accuracy of I_{GSS} registered by the instrument.

Four silicon diode detectors surrounding the DUT were used to monitor the incident ion flux during the various phases of the measurements. The fluence estimated on the basis of their indications is used to check the accuracy of the number of impacting ions counted by means of the fast sampling oscilloscope.

The direction of incidence of the ions was normal to the DUT surface.

3. The experimental results

As a first experiment about the gate damage formation we irradiated the patterned capacitors with ^{79}Br ions accelerated at 223 MeV. The irradiation was repeated on 16 samples that were irradiated with an increasing number of impacting ions. The bias conditions during the irradiation were: $V_{DS} = 40$ V and $V_{GS} = -2$ V.

In Fig. 5, a comparison between the I_{GSS} measured immediately after the exposure is shown. The figure indicates that the I_{GSS} characteristic of the devices irradiated at lower fluences (∼50 ions) is superimposed with the IV characteristic of a fresh device thus indicating that no damage was created in the oxide. At higher fluences

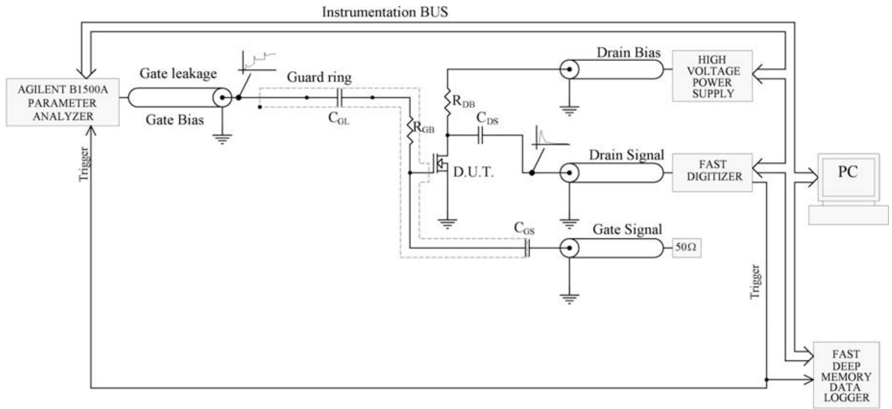

Fig. 4. The experimental set-up used for the experiment.

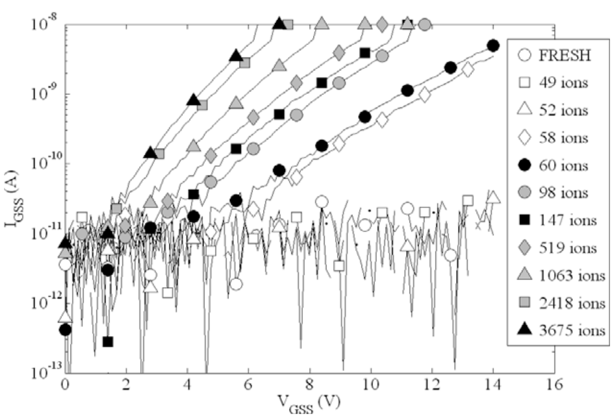

Fig. 5. The I_{GSS} characteristic after the irradiation with ^{79}Br for V_{DS} = 40 V at increasing fluence.

the Fowler–Nordhaim threshold voltage reduced and the slope of the I_{GSS} characteristic increases with the number of impacting ions.

A similar result is obtained at higher values of the bias voltage applied during the irradiation as shown in Fig. 6, that reports the I_{GSS} characteristics measured immediately after the irradiation of six samples with ^{79}Br ions at increasing fluence. The biasing conditions during the irradiation were V_{DS} = 80 V and V_{GS} = −2 V. In this latter case damages were observed even on the sample irradiated with only eight ions whereas with V_{DS} = 40 V samples did not show damages with 50 ions. This indicates that the probability of creating gate damages increases with the voltage applied at the drain during the irradiation.

Also the amount of the gate damage significantly increases with the irradiation bias voltage as shown in Fig. 7, where a comparison between the I_{GSS} measured after the irradiation of three samples with about 1000 ions each at V_{DS} = 40, 60 and 80 V applied during the irradiation.

The patterned capacitors were also irradiated with ^{197}Au ions accelerated at 246 MeV in order to study the dependence of the damage formation with the energy of the impacting ions. In facts gold ions have a large energy loss released in the gate oxide, as indicated in Fig. 1, and then the charge generated by gold within the oxide is larger than that generated by the bromine.

Some experimental results are shown in Fig. 8, which reports I_{GSS} measured immediately after the irradiation with ^{197}Au ions at V_{DS} = 40 V and V_{GS} = −2 V. Nine samples were irradiated with about ten ions each as can be seen from the legend of the figure. The yellow triangles curve of Fig. 8, corresponding to the sample C29, is practically coincident with that one of a fresh device (see Fig. 3), thus indicating that no damage was generated on this sample during the irradiation. All the remaining curves of Fig. 8, have a shape very similar to those ones of the previous figures with the exception of the curves corresponding to the samples C31, C35 and C36, respectively. These latter curves show a significant increase of I_{GSS} at lower values of V_{GSS}.

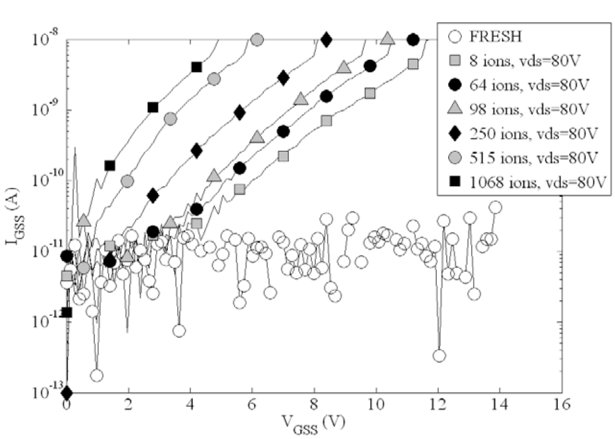

Fig. 6. The I_{GSS} characteristic after the irradiation with ^{79}Br for V_{DS} = 80 V at increasing fluence.

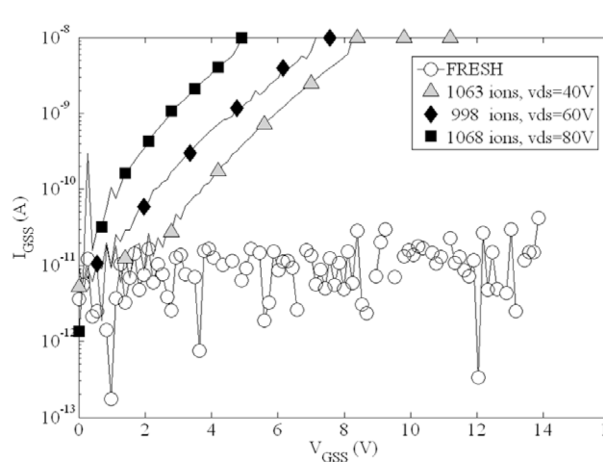

Fig. 7. The I_{GSS} characteristic after the irradiation with about 1000 ^{79}Br ions at V_{DS} increasing between 40 V and 80 V.

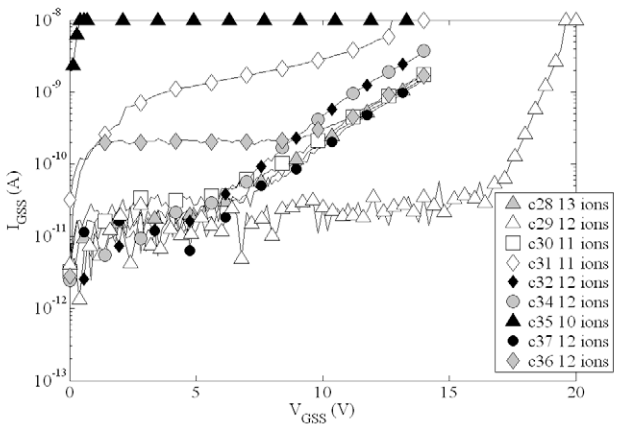

Fig. 8. The I_{GSS} characteristic measured right after the irradiation with about 10 ^{197}Au ions at V_{DS} = 40 V.

We propose to attribute this "strange" increase of the leakage current to the large amount of charge segregated into the oxide as a consequence of the generation of the large number of electron–holes pairs caused by the ion strike. This is a transitory phenomenon and disappears in the time as shown in Fig. 9, which reports the I_{GSS} measured on the same samples after 45 days from the irradiation. The I_{GSS} characteristics become much more regular and the shift of the Fowler–Nordheim threshold is reduced after 45 days of ambient temperature annealing. From Fig. 9, it is worth noting that the I_{GSS} characteristics tend to cluster in four groups:

(1) sample C29, with no damage,
(2) samples C28, C30, C32, C35 and C37, for which $I_{GSS,mean}$ (the mean value of I_{GSS}) = 0.3 nA at V_{GSS} = 14 V,
(3) samples C32 and C34, with $I_{GSS,mean}$ = 0.7 nA at V_{GSS} = 14 V,
(4) sample C31 with I_{GSS} = 1.6 nA at V_{GSS} = 14 V.

This clustering is the strong indication that the shift of the Fowler–Nordheim threshold is a discrete function of the number of impacting ions. In particular we propose that the same number of ions has created damages in the samples of each group. Very likely a single ion has created a single gate damage in each sample of the second group.

The comparison between the results of Figs. 9 and 5, let us also conclude that the probability of creating gate damages is a function of the mass of the impacting ion. In facts after the irradiation at V_{DS} = 40 V no damages were observed in two samples irradiated with about 50 bromine ions instead only one sample had no damage after the irradiation with about 10 gold ions at the same V_{DS}.

In Fig. 10, the I_{GSS} leakage current is reported for four samples irradiated each with about 50 ^{197}Au ions accelerated at 246 MeV. The measures were performed after 45 days from the irradiation. The results of Fig. 10, confirm that the shift of the Fowler–Nordheim threshold is a discrete function of the number of the impacting ions. Moreover, the increase of the gate leakage current is proportional to the number of ions impacting on each sample. In particular, we measure 1.4 nA, 3 nA and 6 nA at V_{GS} = 14 V on the samples irradiated with 50 ions. This sequence directly follows the sequence of 0.3 nA 0.6 nA and 1.6 nA measured at 14 V on sample irradiated with about 10 ions each (see Fig. 9). Also in this case we can assume that a limited and increasing number of impacting ions have induced damages in the gate oxide of the sample of each group.

As it was already observed for the ^{79}Br irradiation in Fig. 7, the increase the biasing voltage V_{DS} applied during the irradiation causes an increase of I_{GSS} also for ^{197}Au irradiation as it is shown in Fig. 11, where the I_{GSS}, measured after 45 days from the irradiation, is reported for five samples irradiated each with about 50 gold ions accelerated at 246 MeV with a biasing voltage V_{DS} = 80 V. The increase of I_{GSS} is much larger than the one observed at V_{DS} = 40 V

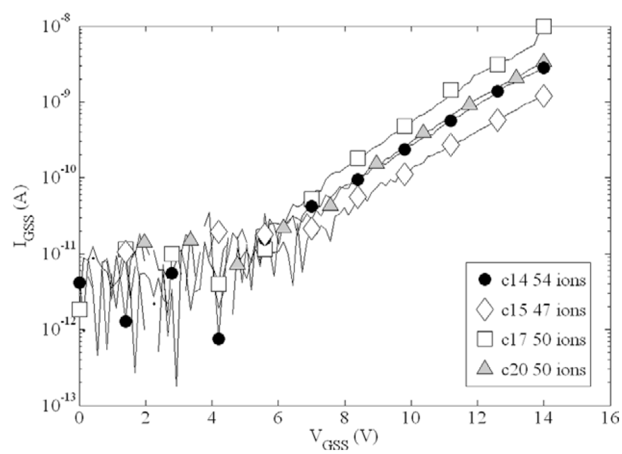

Fig. 10. The I_{GSS} characteristic measured after 45 days from the irradiation with about 50 ^{197}Au ions at V_{DS} = 40 V.

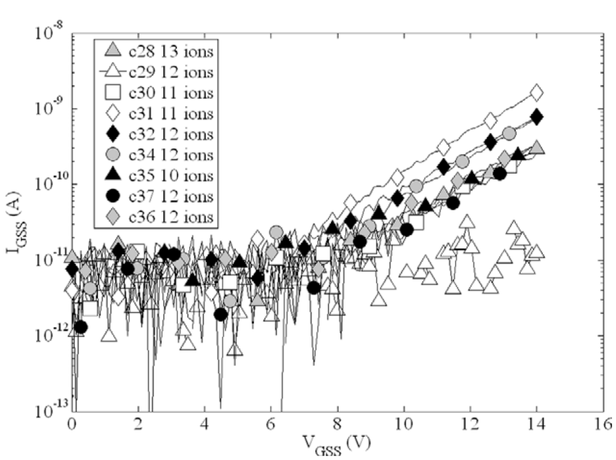

Fig. 9. The I_{GSS} characteristics measured after 45 days from the irradiation with about 10 ^{197}Au ions at V_{DS} = 40 V.

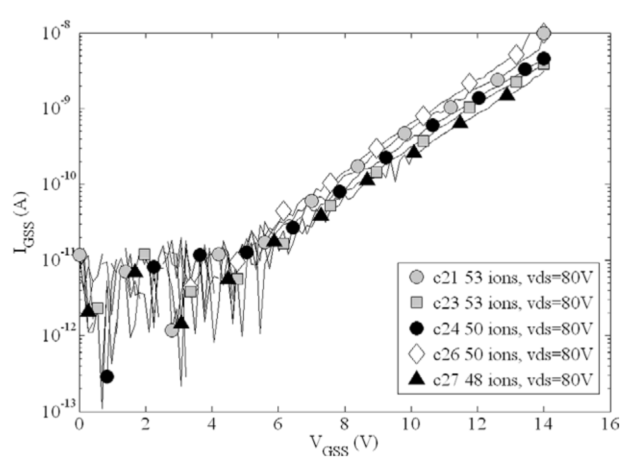

Fig. 11. The I_{GSS} characteristic measured after 45 days from the irradiation with about 50 ^{197}Au ions at V_{DS} = 80 V.

(see Fig. 10) and can be attributed both to the increased probability of creating gate damages and to the larger damage produced by the single impact at a larger biasing voltage.

4. Conclusions

In this paper we have presented the results of an experimental study aimed to investigate the formation of ‘‘latent damages’’ created in the gate oxide during heavy ion irradiation of patterned capacitors derived from 100 V power MOSFETs.

To properly detect the presence of ‘‘latent damages’’ a simple IV static characterization after the irradiation can be performed. The formation of gate damages is revealed by the shift of the Fowler–Nordheim conduction threshold. The amount of this shift is correlated to the amount of the gate damage generated during the impact.

The amount of the damages created increases with the number of the impacting ions, with the drain–source voltage applied during the irradiation and with the mass of the impacting ions. Also the probability of creating gate damage increases with the irradiation biasing drain voltage and with the mass of the impacting ions.

The shift of the Fowler–Nordheim threshold is a discrete function of the number of impacting ions and it is possible to identify the amount of the damage induced by a single particle by performing irradiation experiment with a very low number of impacting ions.

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