PoS PROCEEDINGS OF SCIENCE

Radiation performance of new semiconductor power devices for the LHC experiment upgrades

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GaN and SiC power devices were extensively tested under different types of radiation, in the framework of the APOLLO R&D collaboration, aiming to use these new technologies for designing power supplies for the future LHC experiments upgrades.
SiC power MOSFETs were irradiated with γ-rays, neutrons, and heavy ions (Iodine, Bromine) at different energies (20MeV - 550MeV). They showed very good performances in terms of Total Ionizing Dose (TID) sensitivity, but exhibited a quite poor Safe Operating Area (SOA) with respect to Single Event Effects (SEEs).
Enhancement-mode GaN transistors manufactured by EPC, with blocking voltage ranging from 40V to 200V, were irradiated with γ-rays, heavy ions (Iodine, Bromine), and low energy protons. They showed a very good SOA toward SEE. After the irradiation with 3-MeV protons at the highest fluence ($4 \cdot 10^{14}$ p/cm^2), the devices exhibited an increase of up to one order of magnitude in gate leakage, almost 1 V of threshold voltage reduction, degradation of the subthreshold slope, and drop in transconductance. The reduction in threshold is in contrast with the increase normally observed in GaN devices irradiated with protons, and is likely due to radiation effects in the layers introduced to engineer the positive threshold voltage.

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Introduction

Gallium Nitride and Silicon Carbide-based power devices offer interesting advantages over standard silicon devices, also from a radiation hardness standpoint.

GaN-based HEMTs (High Electron Mobility Transistors) are very attractive thanks to the outstanding properties of Gallium Nitride, a wide bandgap III-V semiconductor material. GaN electronic devices promise to deliver more output power and achieve higher efficiency than transistors made from either silicon or gallium arsenide, due to the wide bandgap (3.4 eV) which enables higher saturated electron velocities and higher breakdown fields.

In addition, bulk GaN material is radiation hard [1]. In fact, the minimum energy to displace GaN atoms is larger than in Si and GaAs, and close to that of SiC. Also Total Ionizing Dose (TID) tolerance is outstanding. The devices exploit the properties of heterostructures, and the channel is formed through band engineering, without the use of dielectric layers underneath the gate, which are Achilles' heel of Si-based power MOSFETs, as far as TID effects are concerned.

At the beginning of the 2000's, the total dose sensitivity of GaN HEMTs was investigated, concluding that the degradation was not appreciable up to very high doses (hundreds of Mrad). The vast majority of the literature on radiation effects in GaN HEMTs deals with displacement damage after proton irradiation. Data show that these GaN-based HEMTs, with few exceptions, are able to withstand proton fluences in excess of 10^{12} p/cm^2 with only minor degradation.

Silicon Carbide is a wide bandgap III-V semiconductor material too and enables higher breakdown fields like GaN. SiC permits to deliver much larger output power than GaN, because in SiC devices the output current flows vertically contrarily to GaN where the current flows along a surface. This characteristic permits to achieve high voltage power devices (Schottky power diodes, MOSFETs rated up to 1.7 kV [2], and bipolar IGBTs rated up to 15 kV [3]) with current capabilities comparable or larger than lower voltage Silicon and GaN devices.

SiC devices have an epitaxial layer much thinner and more doped with respect to silicon devices with comparable blocking voltages so in principle they have a lower sensitive volume to the TID and Single Event Effect (SEE) involving the semiconductor part of the device.

Some works have been dedicated to study SEEs in SiC power diodes [4], power Schottky diodes [5] and MESFETs [6]. TID effects have been studied on SiC BJTs [7] and power MOSFETs [8].

The objective of the present work is to present the results of an extended characterization of GaN and SiC power devices. These devices were tested under different types of radiation, in the framework of the APOLLO R&D collaboration, aiming to verify the possibility of using these new technologies for designing power supplies for the future LHC experiments upgrades.

Devices and Experiments

The irradiation tests were executed at the following irradiation facilities:

- **γ-rays:** at CALLIOPE, ENEA-UTTMAT, Casaccia, Rome, Italy;
- **Neutrons:** at TAPIRO, ENEA, Casaccia, Rome, Italy;
- **Low energy Protons:** at CN accelerator of Laboratori Nazionali di Legnaro (LNL), INFN, Padua, Italy;
- **Heavy ions:** at TANDEM-XTU and TANDEM-ALPI accelerators of the Laboratori Nazionali di Legnaro (LNL), INFN, Padua, Italy.

Sic Power MOSFET

The first set of tested devices include power MOSFET manufactured by CREE on SiC rated at 1200V 24A.

The time durations of the γ-ray irradiations were set to achieve increasing doses (0.57, 1.1, 1.7, 5.2, and 10.8 kGy) using a dose rate of 23.8 Gy/h. After the irradiation the samples were subjected to one week 100°C thermal annealing.

Neutron irradiations were performed with increasing doses: 0.39, 0.68, 0.52, 2.67 10^{12} n/cm^2 1MeV equivalent (Si) with a dose rate of 3.4 10^{11} neutrons/cm^2/h 1MeV equivalent (Si).

During γ-ray irradiations the Devices Under Test (DUTs), were statically biased with V_{GS}=16V (corresponding to 80% of the maximum gate voltage) and V_{DS}=0V.

The neutron irradiations were performed on DUTs biased with V_{DS}=960V (80%di 1200) and V_{GS}=-3V.

A group of SiC power MOSFETs was irradiated with ^{79}Br at energies ranging between 20 and 240MeV (obtained with TANDEM-XTU) and 550MeV (TANDEM-ALPI). During the irradiations DUTs were biased with V_{GS}=0V and V_{DS} increasing up to the failure voltage. The circuit and the test procedure used for heavy ion irradiations, omitted here for brevity, can be found in [9].

GaN HEMT

The second set of tested devices consists of two types of enhancement-mode GaN High Electron Mobility Transistors manufactured by Efficient Power Conversion (EPC). They have a blocking voltage of 40 or 200 V and a maximum continuous I_{DS} of 12 or 33 A, and a maximum pulsed current of 60 or 150 A.

Some GaN HEMTs were irradiated with γ-rays in the same irradiation campaign of SiC power MOSFETs at increasing doses (0.57, 1.1, 1.7, 5.2, and 10.8 kGy) with a dose rate of 23.8 Gy/h and then were subjected to one week 100°C thermal annealing. During the irradiation, DUTs were biased with V_{GS}=5V (corresponding to 80% of the maximum gate voltage) and V_{DS}=0V.

A second group of samples was irradiated with ^{79}Br at 240MeV and with ^{125}I at 300MeV, both obtained with TANDEM-XTU.

Furthermore, a third group of devices was irradiated with low-energy protons at the CN accelerator of the Legnaro National Laboratories (LNL), with a fluence up to $4 \cdot 10^{14}$ p/cm^2. The devices were left unbiased during the exposure. DC parameters have been measured before and after 3-MeV proton irradiation. It is worth to note that the energy of these protons is too low to give rise to secondary particles, so that no indirect SEEs are generated during the exposures. Instead degradation mainly comes from displacement damage.

Results and Discussion

1.1 SiC MOSFETs

The effects of γ-ray irradiations on the characteristics of SiC MOSFETs are summarized in Figs. 1-3 where threshold voltage, R_{on}, and I_{GSS} measured after γ-ray irradiations are reported as a function of the dose absorbed during the irradiation.

Small changes are observed in R_{on} and I_{GSS} up to the highest dose. A significant reduction of the threshold voltage (Fig. 1) is observed at increasing doses down to -0.25V for 10.8 kGy. This significant change does not affect the use of this device in power supplies for the ATLAS upgrade, namely 10kGy. In fact, to guarantee that the device is off a suitable driver able to apply a negative voltage (i.e. -3V) will be required.

SiC power MOSFETs are very robust with respect to the sensitivity to Single Event Effect induced by neutrons. In fact, no Single Event Burnout, SEB, or Single Event Gate Rupture, SEGR, was detected up to 2.7 10^{12} n/cm^2 1MeV equivalent (Si) which is about 20% of the maximum expected dose of ATLAS upgrade, namely 1.6 10^{13} n/cm^2 1MeV equivalent (Si). All the characteristics of the neutron irradiated SiC power MOSFET (threshold voltage, R_{on}, and I_{GSS}) had practically no changes as indicated in Fig. 4 where the threshold voltage measured after irradiations with increasing dose is reported. The measures of R_{on} and I_{GSS} after irradiations are not reported here for brevity.

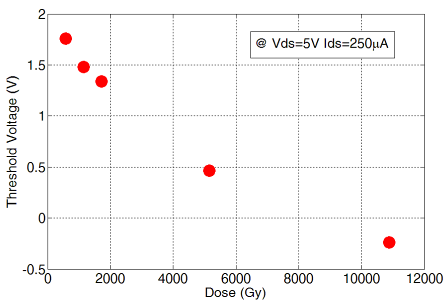

Fig.1. Threshold voltage of SiC MOSFET measured after γ-ray irradiations as a function of the absorbed dose.

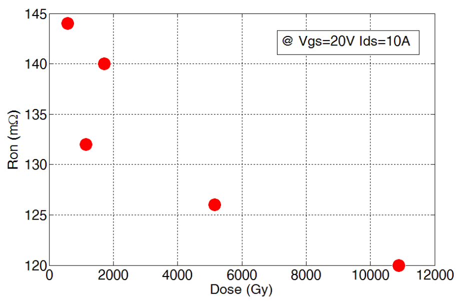

Fig.2. R_{on} of SiC MOSFET measured after γ-ray irradiations as a function of the absorbed dose.

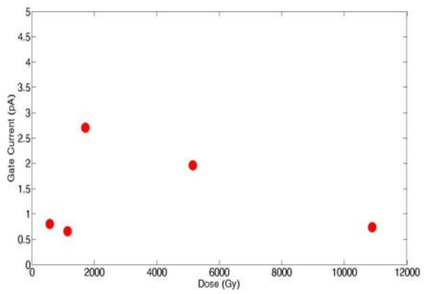

Fig.3. I_{GSS} leakage current of SiC MOSFET measured after γ-ray irradiations as a function of the absorbed dose.

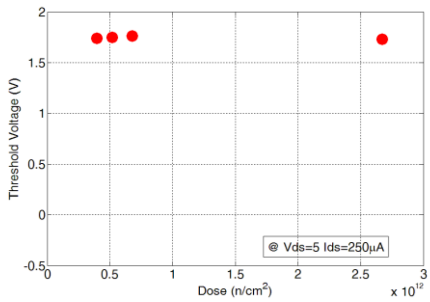

Fig.4. Threshold voltage of SiC MOSFET measured after neutron irradiations as a function of the absorbed dose.

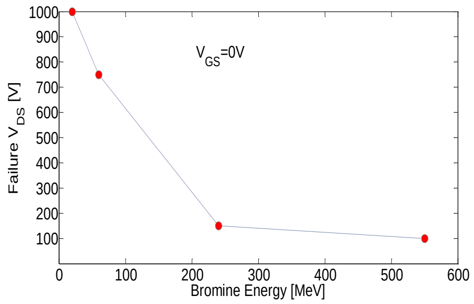

Fig.5. Failure voltage during ^{79}Br irradiations as a function of the beam energy.

SiC power MOSFETs have revealed a significant sensitivity to Single Event Effect induced by heavy ions. In Fig. 5 the failure voltage at which SEB/SEGR were detected during the irradiation with ^{79}Br irradiation at increasing energy is reported.

Fig. 5 indicates that the voltage at which the device can be safely used drastically reduces down to 100V if the devices have a finite probability of being impacted by a highly energetic heavy ion. This limitation does not affect the use of SiC power MOSFET in the ATLAS upgrade for which this probability is very low.

1.2 GaN HEMTs

A first group of GaN HEMTs rated at 40V and 200V were irradiated with ^{79}Br at 240MeV and ^{125}I at 300MeV obtained with TANDEM-XTU. No SEB/SEGR was detected up to the maximum rated voltage both at the drain and gate sides. So we can conclude that these devices have a full Safe Operating Area with respect to SEE. After this result we strongly believe that their sensitivity to SEE induced by neutrons is very good even if the devices have not been tested yet.

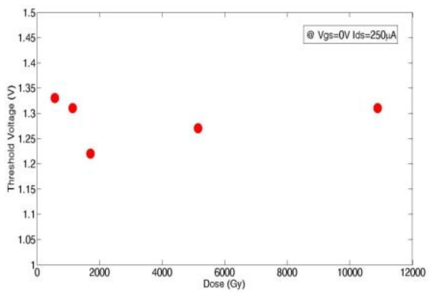

Fig.6. Threshold voltage of GaN HEMT measured after γ-ray irradiations as a function of the absorbed dose.

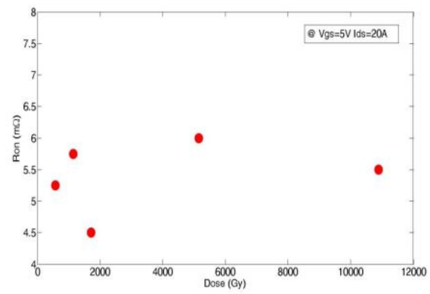

Fig.7. R_{on} of GaN HEMT measured after γ-ray irradiations as a function of the absorbed dose..

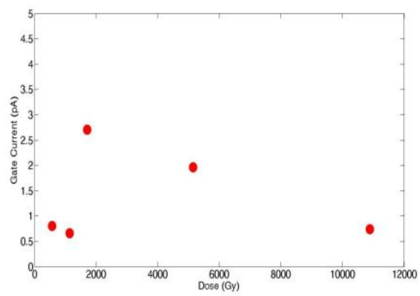

Fig.8. I_{GSS} leakage current of GaN HEMT measured after γ-ray irradiations as a function of the absorbed dose.

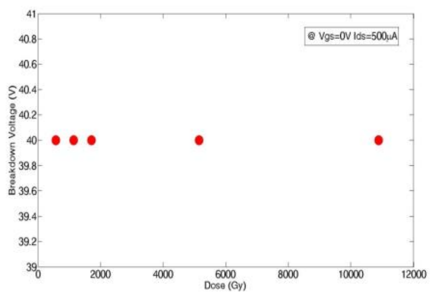

Fig.9. Breakdown Voltage of GaN HEMT measured after γ-ray irradiations as a function of the absorbed dose.

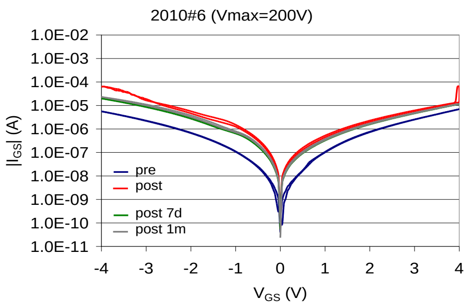

Fig.9. Gate current of an enhancment-mode GaN HEMT irradiated with 10^{14}, 3-MeV p/cm^2.

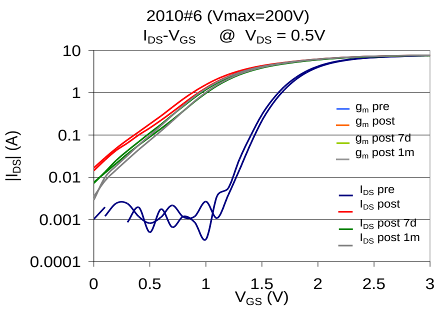

Fig.10. Drain current (log scale) of an enhancment-mode GaN HEMT irradiated with 10^{14}, 3-MeV p/cm^2

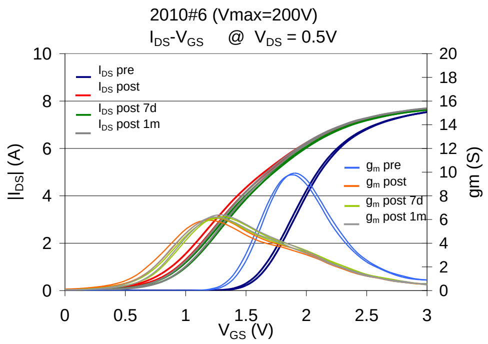

Fig.11. Transconductance and drain current (linear scale) of an enhancment-mode GaN HEMT irradiated with 10^{14}, 3-MeV p/cm^2.

GaN HEMTs have revealed a very good tolerance to total dose radiation effects. In Figs. 6-9, we report threshold voltage, R_{on}, I_{GSS}, and breakdown voltage measured on 40V GaN HEMT after γ-ray irradiations as a function of the dose absorbed during the irradiation. The variation of all above parameters are negligible up to the maximum dose of 10.8 kGy.

GaN HEMTs were irradiated with 3 MeV protons up to a fluence of $4{\cdot}10^{14}$ p/cm^2. After this irradiation, observed effects include:\

- increase in gate current
- threshold voltage reduction
- transconductance drop.

As shown in Fig. 9, the increase in gate current, up to one order of magnitude, is visible at all voltages, but it is more pronounced for negative voltages. It partially anneals during room temperature storage.

Fig. 10 shows the transfer characteristics in logarithmic scale: an unexpected decrease in threshold voltage of about 1V, with a degraded substreshold slope, is visible in the post-rad curves. There is modest recovery during room temperature annealing.

Fig. 11 shows that the peak transconductance drops more than 30% after exposure to 4 $\cdot10^{14}$ p/cm^2. The same figure also shows that the maximum drain current is almost unchanged after irradiation. That is because the threshold voltage reduction offsets the transconductance degradation, resulting in unchanged drive current at the maximum tested gate voltage.

Protons induce both ionization and displacement, so that the observed degradation can result from the superimposition of displacement effects and ionization effects. The maximum total ionizing dose delivered to the samples is almost 5 MGy(Si). However, as shown before, exposures to gamma rays should have minimal impact on the characteristics, meaning that the underlying degradation mechanism is displacement. Yet, much lower ionizing doses were delivered with gamma irradiations (10 kGy(Si)) than with low-energy protons, so no conclusive evidence is available.

In the literature, a decrease in drain current is typically reported on depletion-mode devices irradiated with protons. For instance [10] presents a compilation of several test data over the course of ten years for GaN HEMTs. All devices show decreases in drain current in contrast with the behavior of these enhancement-mode samples. It is not clear if this difference is due to unknown process steps or introduction of other layers.

We also investigated the damage dependence on proton fluence and blocking voltage: the results show a small dependence of degradation on blocking voltage (40V vs 200V) and a small dependence also on proton fluence, accompanied by considerable sample-to-sample variability.

Conclusions

SiC power MOSFET have revealed very good tolerance to γ-rays and neutrons irradiation but they have a low tolerance to SEE induced by high energy heavy ions (^{79}Br). Moreover, enhancement-mode GaN transistors have been tested with γ-rays, heavy ions (^{79}Br and ^{125}I), and low-energy protons and have shown considerable hardness with respect to total dose and displacement damage.

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