Radiation induced degradation of electrical characteristics of III-V devices

A. Paccagnella (1), C. Del Papa (2), P. Chitussi (3), P.G. Fuochi (4),
and P. Benetti (5)

(1) Istituto di Elettrotecnica dell'Università, Cagliari, Italy
(2) Dipartimento di Fisica dell'Università and INFN, Bologna, Italy
(3) Dipartimento di Elettronica e Informatica dell'Università, Padova, Italy
(4) CNR-FRAE, Bologna, Italy
(5) Dipartimento di Chimica Generale dell'Università and INFN, Pavia, Italy

Abstract

The effect of irradiation with gamma rays, electrons or neutrons on the dc and low frequency ac electrical characteristics of III-V FET devices has been studied in this work. The electrical parameters more sensitive to radiation damage have been identified and their behaviour has been compared among the different device types. Pseudomorpfic HEMTs have been found to tolerate radiation exposures better than GaAs MESFETs and AlGaAs/GaAs HEMTs.

I. Introduction

GaAs-based microelectronic devices are suited to face radiation-harsh environments (such as in space or nuclear applications) better than conventional Si components, taking advantage of both higher tolerance of the GaAs substrates toward displacement damage and lacking of MOS-based devices on GaAs [1]. When submitted to high radiation doses, even III-V components will eventually suffer a performance degradation, mainly deriving from the accumulation of lattice damage in the semiconductor substrate [2]. This indicates that particles with high non-ionizing energy loss will be the most harmful for the radiation tolerance of these devices.

In this paper, we have investigated the effects of the exposure to different radiation sources (gamma rays, electrons and neutrons) on the dc and low frequency ac characteristics of three different kinds of FET components: i) GaAs MESFETs; ii) AlGaAs/GaAs HEMTs; iii) AlGaAs/InGaAs pseudomorphic HEMTs, which will be referred to as PM-HEMTs in the following. To the best of our knowledge, this report offers the first data on PM HEMT radiation hardness. The comparative radiation tolerance of such devices will be discussed also in correlation with different testing conditions.

II. Experimental procedures

The different components examined in this work have been acquired from three commercial suppliers. The devices have been exposed to different radiation sources, and kept unbiased during irradiation and subsequent storage periods.

Co^{60} γ irradiation have been performed in a gamma cell with annular geometry, at a dose rate of 7 krad(Si)/min. A LINAC source has been used to generate a pulsed beam of 9 MeV electrons for exposures in air. Neutrons with a fission energy spectrum have been supplied by a nuclear reactor. Doses up to 10 Mrad(Si) from γ, 20 Mrad(Si) from electron irradiation, and neutron fluences up to $10^{14}cm^{-2}$ have been considered in this work. During neutron exposures, devices were encapsulated in a Cd box to prevent activation by thermal neutrons.

The electrical measurements have been performed on each device before and immediately after irradiation, in order to reduce possible annealing effects of the radiation damage. Only in case of the 10^{14} cm^{-2} neutron irradiated devices, 2 weeks elapsed before measurement to ensure a substantial decay of the induced radioactivity level.

III. Results and discussion

A. Drain current

Upon γ irradiation, all devices have shown negligible modifications of the electrical characteristics up to a cumulative dose of 10 Mrad(Si).

If a comparable radiation dose is instead supplied by electron irradiation, a noticeable variation of the main device parameters can be detected, as reported in Figs.1, 2, and 3, for MESFETs, HEMTs, and PM-HEMTs, respectively. The decrease of the output drain current I_{ds} measured at V_{ds}=0.2 V (linear region) and V_{ds}=2 V (saturation region) is reported in these figures for different doses. In all devices, I_{ds} approximately decreases linearly with dose, without any saturation effects, in agreement with previous experimental data [2].

In MESFETs, such behaviour derives from lattice damage in the channel layer which gives rise to: donor compensation due to generation of acceptor states; free carrier removal due to deep level trapping; and mobility decrease due to formation of charged scattering centers [3-5].

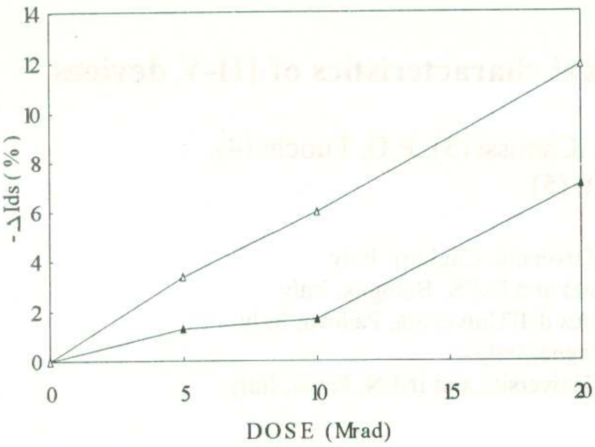

Fig.1. Variations of the drain current of MESFET devices irradiated with 9 MeV electrons. Full symbols: V_{ds}=0.2 V; open symbols: V_{ds}=2 V.

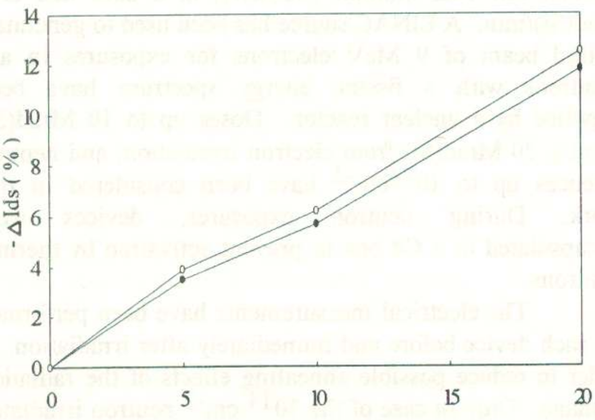

Fig.2. Variations of the drain current of HEMT devices irradiated with 9 MeV electrons. Full symbols: V_{ds}=0.2 V; open symbols: V_{ds}=2 V.

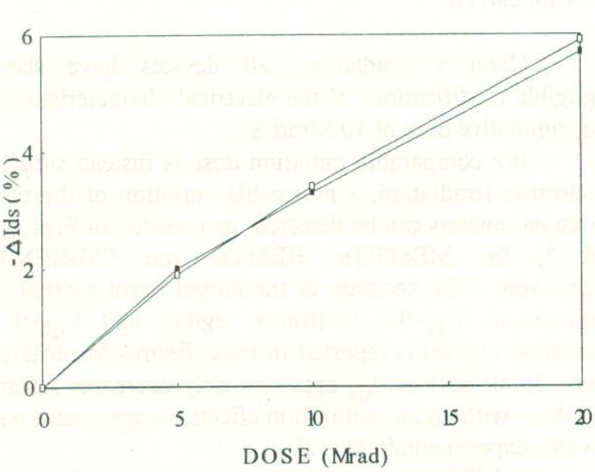

Fig.3. Variations of the drain current of PM HEMT devices irradiated with 9 MeV electrons. Full symbols: V_{ds}=0.2 V; open symbols: V_{ds}=2 V.

In HEMTs, the I_{ds} variations derive from radiation damage of the undoped GaAs layer where the 2DEG is formed, inducing a mobility decrease and an increase of the acceptor concentration [6]. In these devices, the decrease of the donor concentration in the AlGaAs layer gives a negligible contribution to the Ids variations.

In all irradiated devices, the output resistance measured in the linear region at V_{gs}=0 V increases, up to a 15% maximum in HEMTs after the 20 Mrad exposure.

The radiation induced modifications are smaller in the PM-HEMTs, suggesting a better radiation tolerance of the AlGaAs/InGaAs structure and, in particular, of the InGaAs layer. This effect can be favoured by the InGaAs high mobility, which will be less degraded from the introduction of charged scattering centers than the conventional GaAs channel.

In both the HEMT-type devices, the I_{ds} percentual decrease is practically the same in the linear and saturation regimes. Instead, in the MESFET components the I_{ds} variation is smaller at V_{ds}=0.2 V. It can be easily verified [7, 8] that such difference derives from different variations of the pinch-off voltage (see next section). While the mobility degradation linearly affects I_{ds} in both linear and saturated regions, a reduction of $|V_p|$ produces the largest percentual effects on the MESFET saturation current.

After neutron irradiation, the reductions of Ids can be as large as 50%, such as in MESFETs exposed to 10^{14} n/cm^2. Even in this case, the HEMT-type devices show minor percentual degradation than MESFETs.

The radiation induced modifications of I_{ds} show practically no time decay during storage periods at room temperature. The same behaviour has been observed also for all the other parameters considered in this study, indicating the lacking of room temperature annealing phenomena of the radiation damage on a time scale of few months.

B. Pinch-off voltage

The I_{ds} percentual variations just reported are incidentally similar in MESFETs and HEMTs, deriving from the particular device structure: the average pinch-off voltage V_p of our MESFETs is twice as large as the HEMT one. V_p variations after electron irradiation are reported in Fig.4.

Data indicate that modifications are smaller in HEMTs. In fact, HEMT-type devices are expected to offer a higher radiation hardness owing to the separation between free carriers and corresponding donors [9, 10].

Even more dramatic differences arise after high dose neutron irradiation, as reported in Tab.1, owing to the larger extent of displacement damage induced by the neutron flux in the semiconductor lattice. These data confirm that Vp is more sensitive to the radiation damage in MESFET than in HEMT devices: in the first case the donor removal mechanism plays a dominant role, while it doses not ininfluence the HEMT properties.

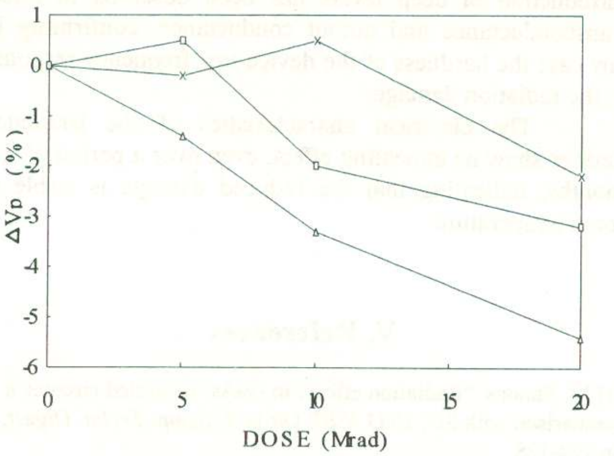

Fig.4. Variations of the pinch-off voltage of the different devices irradiated with 9 MeV electrons. MESFETs: triangles; HEMTs: squares; PM-HEMTs: crosses.

	As received Vp (V)	After 10^{14} n/cm^2 Vp (V)
MESFET	-0.98	-0.77
HEMT	-0.51	-0.45
PM HEMT	-0.58	-0.50

Tab.1. Pinch-off voltage before and after neutron irradiation

C. Transconductance

A decrease of the transconductance g_m has been measured on neutron irradiated devices, in agreement with previous literature data [2, 3]. The effect of electron irradiation appears almost negligible. The g_m degradation mostly derives from a reduction of the free carrier concentration, with some contribution coming from the mobility reduction.

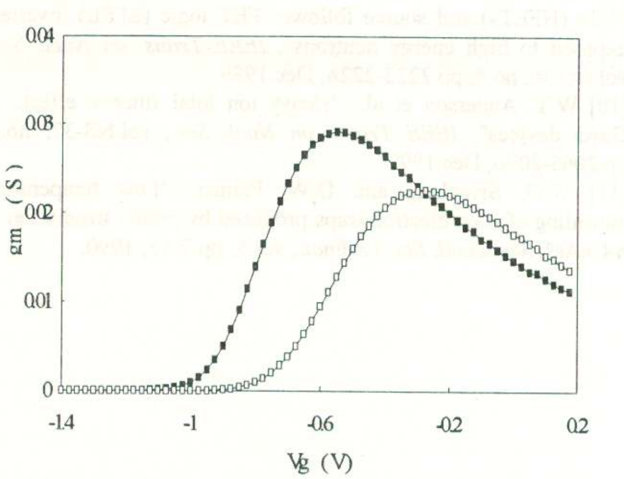

Fig.5. Transconductance of a MESFET device taken at V_{ds}=0.2 V before (full symbols) and after irradiation (open symbols) with 10^{14} n/cm^2.

The net decrease of the channel electron density gives also rise to the shift of the peak g_m toward more positive gate voltage values, as illustrated in Fig.5 for a MESFET exposed to the highest neutron fluence.

No noticeable modification of the frequency dispersion of g_m in the linear region of the device electrical characteristics has been observed after γ, electron, and neutron tests, in the frequency range 10^{-1}-10^{7} Hz, even for measurements at ambient temperatures ranging between -60°C and +60°C. Only a slight increase of the frequency dispersion of the output conductance at high applied drain bias, in the saturation region, has been detected at room temperature. Even gate- and drain-lag measurements have presented no anomalous behaviour after irradiation,

These measurements are very sensitive to frequency dependent anomalies related to deep levels in the channel layer or close to its interfaces. We must conclude that the radiation induced deep levels are unable to follow the input signal in the devices considered. That is, their capture and emission times must be either less than 1 μs (even at -60°C) or longer than 1 s. This constraint seems reasonable for shallow acceptors, and also for such electron traps observed in irradiated GaAs as E1, E2 and E3 levels [11], which lie within 0.32 eV from the conduction band. Alternatively, the deep levels should be placed at energies and in device regions where the applied signal cannot perturb their charge state (e.g., in the depleted AlGaAs HEMT layer). Moreover, irradiation has generated no slow trap at the interface between the III-V semiconductor surface and the passivating dielectric film.

D. Gate diode

A substantial decrease of the gate leakage current has been observed in the irradiated MESFETs, while minor increases have been measured on the HEMT-type devices, as shown in Fig.6. The current was measured between gate and drain (source), with source (drain) kept floating, in order to measure just the Schottky diode reverse current.

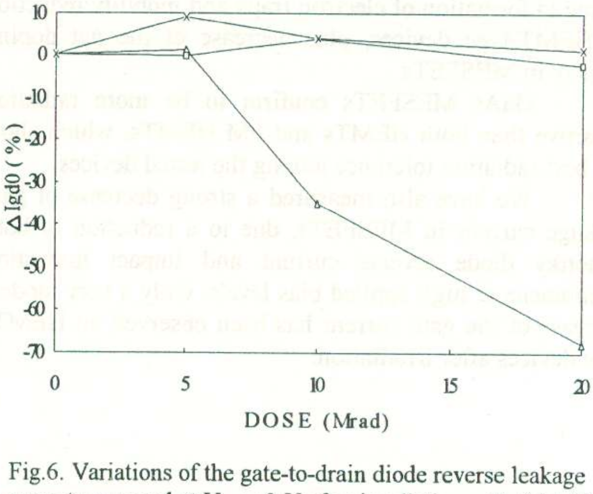

Fig.6. Variations of the gate-to-drain diode reverse leakage current measured at V_{gd}=-2 V after irradiation with 9 MeV electrons. MESFETs: triangles; HEMTs: squares; PM-HEMTs: crosses.

These results indicate that the formation of deep levels does not lead to a large increase of the generation current in the depletion region of the gate contact. Such condition can be verified if radiation induced donor and acceptor levels lie far from midgap, in agreement with the observations quoted in the previous section C.

The decrease of the reverse current of the Schottky diode in MESFETs can be attributed to the reduction of the net doping level in the underlying channel. Even though the doping density before irradiation cannot be evaluated, it is reasonably well over 10^{17} cm^{-3}, thus introducing a tunneling contribution across the Schottky barrier. After irradiation, such tunneling current becomes much reduced due to donor compensation in the channel.

A similar reduction of the gate current Ig has been measured also on irradiated devices biased in the usual working conditions, i.e., Vgs≤0 V, Vds>>0 V. For instance, Ig measured at Vgs=0 V, Vds=2 V (saturation) decreases by almost 90% in MESFETs and only by 4% in HEMTs after 10^{14} n/cm^2. In the saturation region, Ig derives from two contributions: the Schottky diode reverse current and the holes generated by impact ionization of energetic electrons in the channel. The second contribution is obviously stronger for high applied drain bias and intense drain current. Its large decrease in neutron irradiated MESFETs is again originated by electron trapping and doping reduction in the channel region. The modification of the net density of the fixed charge induces in turn a reduction of the local peak of the electric field, and a decrease of the multiplication factor.

IV. Conclusions

The response of III-V FET devices to radiation tests is controlled by the rate of introduction of defects in the active semiconductor layers, and by the device structure. In agreement with previous reports, we have observed a reduction of both drain current and pinch-off voltage, and a shift together with a reduction of the transconductance peak value on all irradiated devices. This is due to formation of electron traps and mobility reduction in HEMT-type devices, plus decrease of the net doping density in MESFETs.

GaAs MESFETs confirm to be more radiation sensitive than both HEMTs and PM HEMTs, which show the best radiation tolerance among the tested devices.

We have also measured a strong decrease of gate leakage current in MESFETs, due to a reduction of both Schottky diode reverse current and impact ionization phenomena at high applied bias levels. Only a very modest increase of the gate current has been observed on HEMT-type devices after irradiation.

No low frequency anomaly related to the introduction of deep levels has been observed to affect transconductance and output conductance, confirming in any case the hardness of the device low frequency response to the radiation damage.

The electrical characteristics of the irradiated devices show no annealing effect, even over a period of few months, indicating that the induced damage is stable at room temperature.

V. References

[1] M. Simons, "Radiation effects in GaAs integrated circuits: a comparison with Si", *1983 IEEE GaAs IC Symp. Techn. Digest*, pp.124-128.

[2] J.Y. Chang, M.H. Badawi, and A. DeCicco, "Neutron/gamma induced damage mechanisms and synergistic effects in GaAs MESFETs", *IEEE Trans. on Nucl. Sci.*, vol.NS-36, no.6, pp.2068-2075, Dec.1989.

[3] M. Nishiguchi et al., "Radiation tolerant GaAs MESFET with a highly-doped thin active layer grown by OMVPE", *IEEE Trans. on Nucl. Sci.*, vol.NS-37, no.6, pp.2071-2075, Dec.1990.

[4] M. Rosenbluth, W.L. Bloss, W.E. Yamada, and B.K. Janousek, "Characteristics of GaAs buffered FET logic (BFL) MESFET's and inverters exposed to high-energy neutrons", *IEEE Trans. on Nucl. Sci.*, vol.NS-38, no.1, pp.20-24, Feb.1991.

[5] W.T. Anderson, M. Simons, and W.F. Tseng, "Long term transient radiation response of GaAs FETs fabricated on an AlGaAs buffer layer", *IEEE Trans. on Nucl. Sci.*, vol.NS-33, no.6, pp.1442-1446, Dec.1986.

[6] R.J. Krantz, W.L. Bloss, and M.J. O'Loughlin, "Neutron degradation of the I-V characteristics of AlGaAs/GaAs modulation-doped field-effect transistors", *IEEE Trans. on Nucl. Sci.*, vol.NS-38, no.2, pp.858-860, Apr.1991.

[7] M.B. Das, "HEMT device physics and models", in *HEMTs and HBTs: Devices, fabrication, and circuits*, Fazal Ali and Aditya Gupta eds., Artech House, Boston, 1991.

[8] D.L. Pulfrey and N. Garry Tarr, *Introduction to microelectronic devices*, Prentice-Hall International, London, 1989

[9] B.K. Janousek et al., "Characteristics of GaAs heterojunction FETs (HFETs) and source follower FET logic (SFFL) inverters exposed to high energy neutrons", *IEEE Trans. on Nucl. Sci.*, vol.NS-36, no.6, pp.2223-2228, Dec.1989

[10] W.T. Anderson et al., "Heavy ion total fluence effects in GaAs devices", *IEEE Trans. on Nucl. Sci.*, vol.NS-37, no.6, pp.2065-2070, Dec.1990

[11] W.O. Siyanbola and D.W. Palmer, "Low temperature annealing of deep electron traps produced by proton irradiation of n-GaAs", *Semicond. Sci. Technol.*, vol.5, pp.7-15, 1990.