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Power improvement of AlGaAs/InGaAs PHEMTs by using low gamma radiation dose

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ABSTRACT

This paper shows the possibility to improve DC and RF electrical performances of AlGaAs/InGaAs PHEMTs by using low gamma radiation dose. The drain–source saturation current and the DC transconductance increase when the devices are irradiated with a gamma dose of 42.8 krad(GaAs) and then remain constant up to 0.85 Mrad(GaAs). This improvement is attributed to a reduction of access resistances. In the same time, the Schottky diode and the current-gain cut-off frequency of these components are not degraded by the gamma irradiation. Moreover, the maximum output power density is improved by 18%. This paper demonstrates that it is possible to improve the component electrical performances by using an original method.

1. Introduction

GaAs-based Field Effect Transistors (FET), and in particular the Pseudomorphic High Electron Mobility Transistors (PHEMTs), are extensively used for millimeter-wave and optical communication systems due to their excellent high frequency and low-noise performances [1–3]. PHEMTs can also be used for power applications because they have higher power gain than conventional Metal Semiconductor Field Effect Transistors (MESFETs) [4,5].

As these GaAs-based devices are intended to be used in satellite communication systems, military and nuclear industry [6], it is imperative to study their electrical and microwave behaviors in extreme radiation environments [7]. Most of previous papers have studied the neutron [8–10], gamma [11], and proton [12] radiation effects on the electrical behaviors of these devices. In general, the purpose of these studies is to show the high immunity of these transistors to radiation-induced degradations. In fact, electrical parameters as threshold voltage (V_{th}), drain–source saturation current (I_{DSS}), and transconductance (g_m) are not subjected to drastic evolution at doses up to 1×10^8 rad(Si) [13–15].

So, Luo et al. have studied the effects of gamma-ray irradiation on GaAs MESFETs DC characteristics. They have shown that the sheet resistance was linearly proportional to the radiation dose higher than 557 Mrad (the unit for gamma dose is not specified with respect to the material in which the radiation is absorbed). They have also shown that the drain–source saturation current decreased for a radiation dose higher than 169 Mrad [6]. Gromov et al. have displayed that the drain–source current of a GaAs-based PHEMT is slightly degraded for a gamma radiation dose of 3×10^5 rad(GaAs). They have also observed a consistent performance degradation for doses higher than 1×10^8 rad(GaAs). The same PHEMTs irradiated by X-ray exhibit increasingly better performances as the dose is raised [11]. But, they have not studied the influence of radiation effects on the RF electrical performances.

However, Konakova et al. have observed an improvement of the ohmic contacts performed on GaAs/AlGaAs heterostructures for gamma irradiation dose close to 2.5×10^7 rad(GaAs) [16,17].

Furthermore, the impact of gamma rays on the electrical performances of GaAs-based devices is closely linked to the epitaxial structure, sample quality, doping level, and device processing [17–19]. Besides, Gromov et al. have shown that the immunity to irradiation induced degradation was different for normally-on MESFETs, normally-off MESFETs, normally-on PHEMTs, and normally-off PHEMTs [11]. For example, the drop of the drain–source current for a normally-on MESFETs is less important than for a normally-on PHEMTs after a gamma irradiation with a dose of 1×10^7 rad(GaAs).

Complementary to previous studies [11,16,17], we have investigated here, the influence of low gamma radiation doses on DC and RF electrical performances of AlGaAs/InGaAs PHEMTs. Moreover, the technology of AlGaAs/InGaAs devices is mature and industrialized.

2. Device fabrication

The AlGaAs/InGaAs PHEMT structure was grown by Molecular Beam Epitaxy (MBE) on a semi insulating GaAs substrate (Fig. 1).

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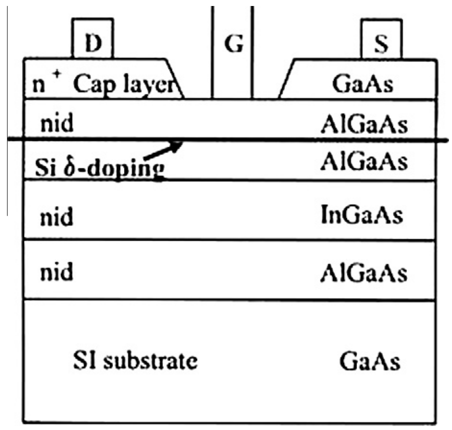

Fig. 1. Structure of the AlGaAs/InGaAs PHEMTs.

It consists of an AlGaAs buffer, an InGaAs channel with In mole fraction of 30%, an AlGaAs barrier including a Si δ-doping and a spacer, and a highly doped GaAs cap layer. Device processing began with source and drain ohmic contacts formation using Ni/AuGe/Ni/Au followed by a boron implantation for the device isolation. Al/Ni/Au gate was defined by E-beam lithography and was deposited after the cap was selectively etched away. Then, the devices were passivated using SiN_X dielectric but were not encapsulated. The gate length was 0.25 μm and the device width was 50 μm per finger with 8 fingers per component. This study has been realized with five components.

The gamma irradiations were performed at CEA–INSTN (Commissariat à l'Energie Atomique – Institut National des Sciences et Techniques Nucléaires) in Cherbourg-Octeville (France) on unbiased devices using a ^{137}Cs source providing a dose rate of 430 rad(GaAs)/h, with cumulative doses up to 0.85 Mrad(GaAs).

3. Results and discussions

3.1. DC characteristics

Fig. 2 presents the $I_{DS}(V_{DS})$ DC characteristics of AlGaAs/InGaAs PHEMTs before and after a gamma irradiation using a dose of 42.8 krad(GaAs). These characterizations were carried out for a drain–source voltage increasing from 0 up to 3 V and for a gate-source voltage varying from −0.6 up to 0.4 V, in steps of 0.2 V.

After irradiation, we can observe an increase of the maximum drain–source current (I_{DSmax}) from 126 up to 134 mA for a drain–source voltage V_{DS} equal to 2.5 V and for a gate-source voltage V_{GS} of 0.4 V. Furthermore, the knee voltage (V_k) decreases from 0.60 down to 0.42 V close to a reduction of 30%. Non-irradiated devices have been measured several months after the first electrical characterizations and the electrical characteristics were exactly the same. Moreover, this study was realized with an accuracy of 1 μA for the current measurements and 10 mV for the voltage measurements. Then these drifts are not due to measurement artifacts.

Then, the GaAs-based devices were exposed to a cumulative gamma radiation dose of 0.85 Mrad(GaAs) (Fig. 3). After the increase of I_{DSmax} with the decrease of V_k, we can notice that I_{DSmax} and V_k remain stable up to the higher dose used in this study. The pinch-off voltage (V_p) defined as the extrapolation of the pseudolinear part of the $I_{DS}(V_{GS})$ characteristics, at V_{DS} = 3 V, to I_{DS} = 0 mA is equal to −0.8 V. After gamma irradiation V_p remains constant up to a cumulative dose of 0.85 Mrad(GaAs).

The maximum DC transconductance (g_m) increases from 415 up to 438 mS/mm after a gamma rays dose of 42.8 krad(GaAs) (Fig. 4) and then remains stable up to 0.85 Mrad(GaAs). We can also observe that the $g_m(V_{GS})$ characteristic obtained after gamma irradiation is slightly wider than before. Then, the linearity performances of the AlGaAs/InGaAs PHEMTs would have to be better after irradiation using a gamma dose lesser than 0.85 Mrad(GaAs). The improvement of the transconductance is in agreement with the increase of the drain–source current which is observed in Fig. 2 after gamma irradiation.

The impact of the gamma irradiation on the ideality factor (η) and built-in voltage (V_b) has been investigated to study the stability of the Schottky contact. The parameters have been extracted from by fitting the current–voltage curve of the Schottky contact under forward bias to a thermoionic emission model [20]. We have estimated the ideality factor with a precision of 0.1. So, Fig. 5 shows that the $I_{GS}(V_{GS})$ characteristics before and after gamma irradiation are identical. We can deduce from Fig. 5 that the ideality

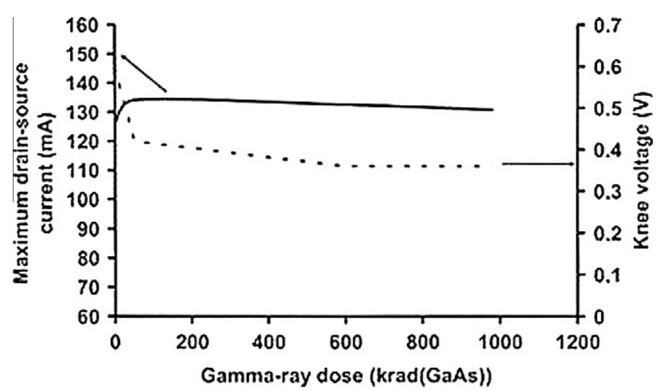

Fig. 3. Evolution of the maximum drain–source current and the knee voltage versus gamma ray cumulative dose.

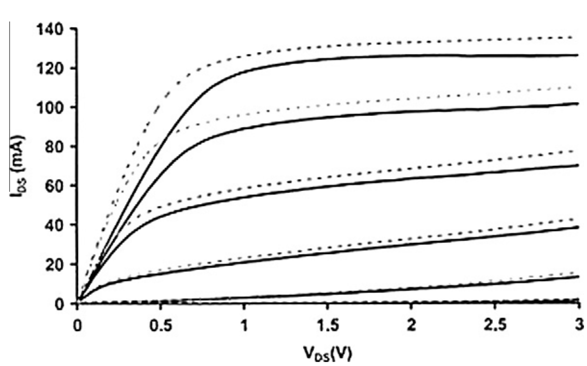

Fig. 2. $I_{DS}(V_{DS})$ characteristics of AlGaAs/InGaAs PHEMTs before (solid line) and after a gamma radiation using a dose of 42.8 krad(GaAs) (dotted line).

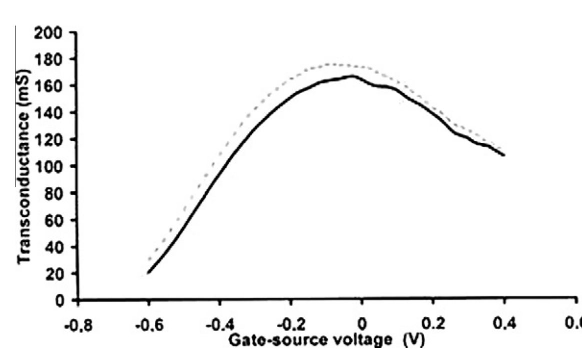

Fig. 4. DC transfer plot (solid line) and after a gamma radiation dose of 42.8 krad(GaAs) (dotted line).

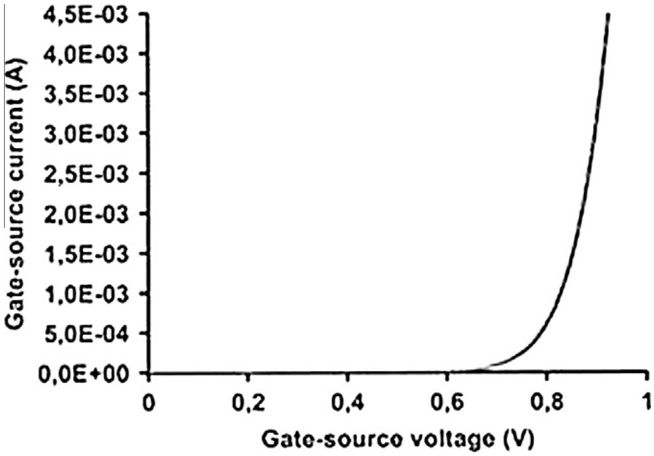

Fig. 5. Evolution of the $I_{GS}(V_{GS})$ characteristics plot before (dotted line) and after a gamma radiation dose of 0.85 Mrad(GaAs) (dotted line).

factor and the built-in voltage remain about 1.6 and 0.8 V, respectively, until a gamma radiation dose of 0.85 Mrad(GaAs). As the ideality factor, built-in voltage, and pinch-off voltage remain constant, we can conclude that the Schottky contact of the AlGaAs/InGaAs PHEMTs remains undamaged by gamma irradiation using a dose up to 0.85 Mrad(GaAs). The results confirm that the gamma irradiation has no influence neither on the command of channel carriers nor on the forward gate current. We have also measured the gate current, I_{GS}, as a function of V_{GS} at higher V_{DS} values (3 V) where the device is operating near the hot electron regime. So, under such bias conditions, the Schottky contact is much solicited. After a gamma irradiation using a dose of 42.8 krad(GaAs), $|I_{GS}|$ leakage current decreases for a gate-source voltage inferior to 0.2 V as shown in Fig. 6. The gate leakage current remains constant up to a cumulative radiation dose of 0.85 Mrad(GaAs).

To complete this work, we have also studied the impact of low gamma radiation doses on the RF performances of these devices.

3.2. RF characteristics

As AlGaAs/InGaAs PHEMTs devices are devoted to power and millimeter-wave applications, we have studied the effects of a gamma irradiation on the gain current cut-off frequency and on the output power density.

The *S*-parameters for AlGaAs/InGaAs PHEMTs devices were measured on wafer using a 40 GHz Network Analyser E8364B.

The cut-off frequency of current-gain was extracted from the *S* parameter measurements by extrapolating $|H_{21}|^2$ with a slope of −20 dB per decade. In these conditions, a value of 53 GHz was obtained.

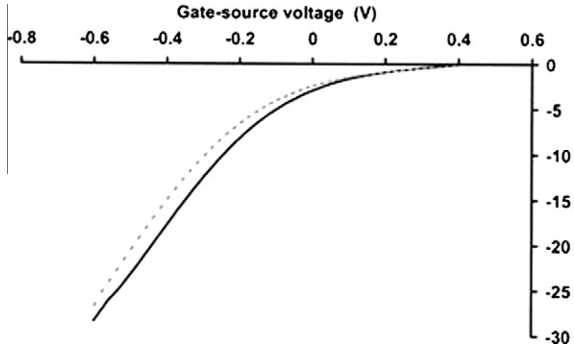

Fig. 6. Evolution of the gate-source current versus the gate-source voltage before (solid line) and after a gamma radiation dose of 42.8 krad(GaAs) (dotted line).

As shown in Fig. 7, no significant degradation of the current-gain cut-off frequency is observable after a gamma radiation dose of 0.85 Mrad(GaAs). These measurements have been performed at V_{DS} = 3 V and V_{GS} = −0.2 V.

We can also speculate that the output power density delivered by the AlGaAs/InGaAs PHEMTs has to be increased after a low gamma radiation dose exposure. In fact, the expected output power density (P_{exp}) can be estimated from the $I_{DS}(V_{DS})$ characteristics of the AlGaAs/InGaAs PHEMTs and is given by [21]:

$$P_{exp} = \frac{\Delta V \cdot \Delta I}{8} \quad (1)$$

where $\Delta V = 2\cdot(V_{max} - V_k)$ and $\Delta I = I_{DSmax}$. In our study, we have observed after gamma irradiation that the maximum drain–source current (I_{DSmax}) increases and the knee voltage (V_k) decreases. Supposing that the maximum drain–source voltage (V_{max}) does not decrease after gamma irradiation, then P_{exp} must also increase. We can deduce from Fig. 2 that the expected output power density could have an increase of 15% when the device is irradiated with a dose of 42.8 krad(GaAs).

This device has been measured at 10 GHz with an active load–pull system using microwave probes. The maximum output power has been obtained at V_{DS} = 3 V and V_{GS} = −0.3 V. Fig. 8a and b present the evolution of the output power, power-added efficiency, and power gain versus absorbed input power for non-irradiated and irradiated devices, respectively. The maximum output power reaches 165 mW/mm at 10 GHz, the respective power gain is about 10 dB, and the associated power-added efficiency is about 37% for the non-irradiated component. The maximum output power of AlGaAs/InGaAs PHEMTs increases up to 194 mW/mm at 10 GHz, the respective power gain remains equal to 10 dB, and the associated power-added efficiency is about 39% when the device is irradiated with a gamma radiation dose of 42.8 krad(GaAs). All these parameters remain constant up to 0.85 Mrad(GaAs).

The RF measurements show that the power performances increase of 18% (from 165 mW/mm up to 194 mW/mm at 10 GHz) with a radiation fluence of 42.8 krad(GaAs). This maximum output power improvement is in total agreement with the value estimated from $I_{DS}(V_{DS})$ DC characteristics and proves that V_{max} does not decrease for the gamma radiation dose we used.

Five components have been measured before and after irradiation and the observations depicted in Figs. 2–8 affect all the components. Moreover, the same results have been observed for many on wafer devices.

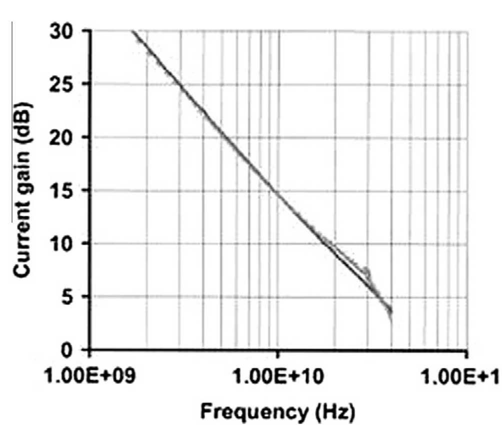

Fig. 7. Evolution of the current-gain versus frequency before (dark line) and after a gamma radiation dose of 0.85 Mrad(GaAs) (light line).

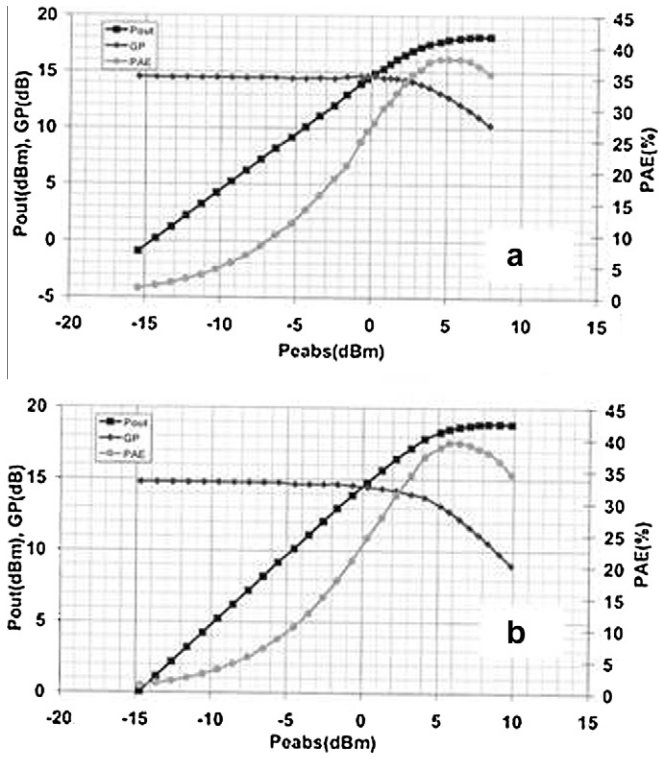

Fig. 8. Evolution of the output power, power-added efficiency, and power gain versus absorber input power for a non-irradiated device (a) and for a device after a gamma radiation dose of 0.85 Mrad(GaAs) (b).

3.3. Discussion

In this paper and for the gamma radiation dose range we used, we have shown that the DC and RF electrical performances of AlGaAs/InGaAs PHEMTs were improved. In fact, a low gamma radiation dose generates a decrease of the knee voltage, an increase of the drain current and consequently an increase of the RF output power while the Schottky contact and the current-gain cut-off frequency remain stable.

As we have reported in the introduction, in the most of previous studies, the only observed modifications of the electrical performances of gamma irradiated devices were degradations [6,15,18,19,22–25]. In fact, the gamma irradiation can cause displacement damages [26], an increase of the sheet resistances which is due to the formation of defects [6], a fall of the maximum drain–source current I_{DSmax} explained by the formation of electron trap centers within the active channel of GaAs MESFETs [6]. In these conditions, these assumptions can justify some gamma irradiation degradations as a reduction of carrier concentration and/or carrier mobility. However, these degradation mechanisms appear for gamma radiation doses higher than 10 Mrad(GaAs) [6,18,19,22] while the higher gamma radiation dose we used in this study is only 0.85 Mrad(GaAs). Furthermore, Gromov et al. have observed a small deterioration of the drain current after a gamma radiation dose of 0.30 Mrad(GaAs) for a GaAs-based PHEMT [11]. This result can be explained by the fact that we used a different PHEMT structure in term of doping rate and In mole fraction of the InGaAs channel (30% versus 17% for Gromov et al.) and also a different technology in term of ohmic contacts and gate metallizations [11].

The observed evolution of the knee voltage and of the maximum drain–source current versus the gamma radiation dose could be explained by three assumptions:

- The highest gamma radiation dose used in this study could be not high enough to lead a fatal displacement damage but it could be sufficient to relax the stress at the heterointerface. Then the region of two dimensional electron gas should experience an raise in carrier density. However, the gamma radiation dose (<42.8 krad(GaAs)) responsible for the improvement of the electrical performances of PHEMTs is too low to induce a stress relaxation at the heterointerface.
- This phenomenon could also be explained by a modification of electrical traps. It has been reported that a low dose radiation introduces a shallow defect which lies about 20 meV below the conduction band and acts as a donor [19]. This defect could be responsible for the increase of the drain current. But, the creation of electrical traps introduced by a gamma irradiation would decrease the RF performances in opposite to our observations.

  The gamma irradiation could also provoke an improvement of electrical performances by reducing the acceptor traps. In this case, the cut-off frequency should increase in opposite to our observations.
- The enhancement of the drain–source current (Fig. 2) cannot be only explained by an increase of the carrier concentration although the drain–source current is proportional to the carrier concentration, because a collapse of the knee voltage is also observed. In fact, the knee voltage is given by the following equation:

$$V_k = (R_D + R_S) \cdot I_{DS} \tag{2}$$

where R_D and R_S are the drain and source access resistances, respectively.

Eq. (2) shows that the reduction of the knee voltage is only possible if the resistances R_D and R_S decrease when I_{DS} increases after gamma irradiation.

The access resistances are defined as follows:

$$R_{access} = R_c + \frac{R_{sheet} L_{DS}}{W} \tag{3}$$

where R_c is the ohmic contact resistance, R_{sheet} is the sheet resistance of the semiconductor, L_{DS} is the drain–source distance and W is the gate width.

Assuming that the gate geometry is not influenced by radiation-induced degradations, Eq. (3) confirms that a reduction of access resistances R_{access} (R_D and/or R_S) is also linked to a reduction of the ohmic resistances and/or the sheet resistance.

The increase of the drain current and the decrease of the knee voltage could be explained by a mechanism of radiation-stimulated structural-impurity ordering at the interface of ohmic contacts with gallium arsenide material. Moreover, the gamma irradiations cause the diffusion of the metals constituting the ohmic contacts (Ni, AuGe, Au) to form a metal layer with a lower resistivity at the interface between the semiconductor and the metal composite. In these conditions, the ohmic contact resistance R_c is reduced. The same phenomenon has been previously observed by Konakova et al. [16,17] with Au/AuGe ohmic contacts performed on a GaAs layer for a Schottky Barrier Field Effect Transistor (SB-FET). So, they showed an enhancement of SB-FET saturation drain current within the range of gamma radiation dose from 4.1×10^6 up to 4.1×10^7 rad(GaAs). They deduced that this improvement of static electrical performances could also be explained by a mechanism of radiation-stimulated structural-impurity ordering at the interface of ohmic contacts with gallium arsenide.

The reduction of the gate leakage current could be explained by the formation of acceptors induced by irradiation would be responsible of a drop of the drain–source current in opposite to our observations. Moreover, an enhancement of the gate usually involves a decrease of the pinch-off voltage but we have shown that V_p remains constant after gamma irradiation. In these conditions, we can say that gamma irradiation does not change the quality of the Schottky contact and that the reduction of the leakage current is linked to the improvement of the ohmic contacts which is solicited during the $I_{GS}(V_{GS})$ characterization.

As the Schottky contact is not influenced by gamma irradiation, we can conclude that the sheet resistance of the semiconductor stays constant because an evolution of R_{sheet} would induce changes of the gate barrier height. So, the reduction of the knee voltage and the increase of the drain current are explained by a decrease of the ohmic contacts R_C.

4. Conclusion

In this paper, we have shown that it is possible to improve the DC and RF electrical performances of AlGaAs/InGaAs PHEMTs by irradiating these components with a gamma radiation dose of 42.8 krad(GaAs). In these conditions, the maximum drain–source current and the maximum transconductance are increased from 124 up to 136 mA, and from 415 up to 438 mS/mm, respectively. This improvement is explained by a reduction of access resistances. In the same time, the knee voltage is reduced by about 30%, the pinch-off voltage, the ideality factor and the built-in voltage remain constant, indicating a non damaged effect for the gate.

Concerning the RF performances, we have observed the stability of the current-gain cut-off frequency and the improvement of the output power density at 10 GHz. So, this is a very interesting method which permits to increase the output power density of 18%.

The DC and RF electrical performances remain stable up to a radiation dose of 0.85 Mrad(GaAs). This phenomenon turns out to be very interesting for microwaves applications.

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