Influence of Thermal and Fast Neutron Irradiation on dc Electrical Performances of AlGaN/GaN Transistors

Fanny Berthet, Yannick Guhel, Bertrand Boudart, *Member, IEEE*, H. Gualous, J. L. Trolet, M. Piccione, and C. Gaquière

***Abstract*—The influence of thermal neutron irradiation and fast neutron irradiation on the electrical properties of AlGaN/GaN HEMTs is investigated. An increase in the drain current and a decrease in the access resistances are observed when devices are irradiated with a thermalized neutrons fluence of 4.3×10^{10} neutrons.cm^{-2} while no evolution is observed with the same fluence of fast neutrons. However, the same phenomenon is observed when the fast neutron fluence is higher (1.8×10^{12} neutrons.cm^{-2}). AlGaN/GaN heterojunctions are analyzed by gamma spectroscopy after thermalized or fast neutron irradiations to understand the physical mechanisms induced by irradiations. In fact, we have shown that the improvement of electrical properties of devices after thermal neutrons irradiation is linked to a Ga-Ge transmutation effect. Moreover, the evolution of the drain current and access resistance when the AlGaN/GaN heterojunctions are irradiated by fast neutrons can be induced by N vacancies creation and/or a change of the strain state of the layers and/or Ga-Ge transmutation effect.**

***Index Terms*—GaN, HEMT, neutron radiation effects, transmutation.**

I. Introduction

AlGaN/GAN high electron mobility transistors (HEMTs) have received increased attention because of their great potential for microwave power devices, and recently, very high power densities have been obtained (> 10 W/mm) on SiC substrate [1], [2]. To ensure the reliable operation of AlGaN/GaN HEMTs for high power amplifiers in a variety of military and space applications, it is essential to demonstrate high reliability performance.

Manuscript received May 31, 2012; revised July 11, 2012; accepted July 16, 2012. Date of publication September 06, 2012; date of current version October 09, 2012.

F. Berthet is with the Laboratoire Universitaire des Sciences Appliquées de Cherbourg, Université de Caen Basse-Normandie, Site Universitaire, 50130 Cherbourg-Octeville, France and also with the Ecole des Applications Militaires de l'Energie Atomique, Cherbourg Armées 50115, France (e-mail: fanny.berthet@gmail.com).

F. Berthet, Y. Guhel, B. Boudart, and H. Gualous are with the Laboratoire Universitaire des Sciences Appliquées de Cherbourg, Université de Caen Basse-Normandie, Site Universitaire, 50130 Cherbourg-Octeville, France (e-mail: fanny.berthet@gmail.com; yannick.guhel@unicaen.fr; bertrand.boudart@unicaen.fr).

J. L. Trolet, and M. Piccione are with the Ecole des Applications Militaires de l'Energie Atomique, Cherbourg Armées 50115, France.

C. Gaquière is with the Institut d'Electronique, de Microélectronique et de Nanotechnologie, Cité scientifique, BP 60069, 59652 Villeneuve d'Ascq, France.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TNS.2012.2209894

As these GaN-based devices are intended to be used in military, nuclear industry, and space applications [3], it is imperative to study their electrical and microwave behaviors in extreme conditions. In fact some of these applications require the device to remain operable after irradiation with high doses of electrons, protons, neutrons or gamma rays [4]. In this paper, we were interested in the impact of neutron irradiation on electrical characteristics of AlGaN/GaN HEMTs. However, a neutron interaction with matter depends on their energies and their fluencies. Neutrons can be overall classified in three categories depending on their energy:

— Thermal neutrons (< 1 eV);
— Epithermal neutrons (1 eV $- 0.8$ MeV);
— Fast neutrons (> 0.8 MeV).

Usually, the majority of papers reported in the literature relates to studies about fast neutron radiation effects on the electrical properties of AlGaN/GaN transistors. In fact Polyakov *et al.* have shown that the mobility and sheet conductivity start to decrease only after a fast neutron fluence superior to 1×10^{15} neutrons.cm^{-2} [4]. The impacts on the carriers mobility are mostly due to the introduction of additional scattering centers in the GaN buffer layer of AlGaN/GaN structures while there are only slight changes in the two-dimensional electron concentration [4]. This paper shows that neutron irradiation introduces electron traps with activation energies of 0.35 and 0.45 eV in AlGaN barrier and hole traps with activation energies of 0.26, 0.6 and 1 eV either in the GaN buffer or in the AlGaN barrier [4]. Zhang *et al.* have reported that the sheet carrier density remains stable after a neutron irradiation with a fluence of 6.13×10^{15} neutrons/cm^{-2} [5]. However, the sheet carrier density decreases slightly when the fluence increases up to 3.66×10^{16} neutrons/cm^{-2} [5]. In this case, the thermal-fast neutron ($E > 1$ MeV) ratio is 6.1:1. We can specify that Polyakov *et al.* have shown that carrier density slightly increases when the fast neutron fluence is inferior to 2.5×10^{16} neutrons/cm^{-2} [6]. But the carrier density drops dramatically by about 40% after an irradiation with a fluence of 1.7×10^{17} neutrons/cm^{-2} [6]. McClory *et al.* have highlighted a decrease in the drain current and an increase in the gate current after fast neutron irradiation with fluencies higher than 6×10^{12} and 3×10^{10} neutrons.cm^{-2}, respectively [7]. They conclude that the increase in the gate current is linked to the formation of traps or defects in the AlGaN layer, which supports the trap, assisted tunneling effects. A decrease in the drain current suggests the formation of interface traps that also reduce the channel mobility [7]. Petrosky *et al.* have also shown that a neutron irradiation affects the gate cur-

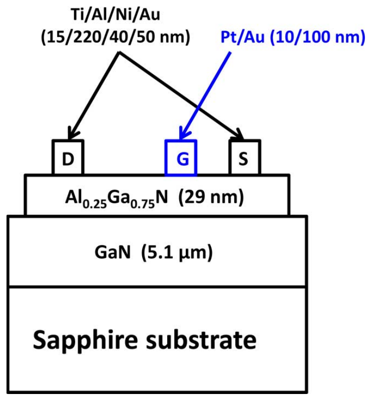

Fig. 1. Devices cross section.

rent through the formation of point defects in the Schottky barrier that facilitate the trap assisted tunneling effects [8].

However, some publications show that the effects induced by neutron irradiations are different according to the radiation carried out by fast neutrons or thermal neutrons [9]. Kuriyama *et al.* highlighted that fast neutron irradiation with a fluence of 6.7×10^{18} $\mathrm{neutrons.cm^{-2}}$ approximately produced 1.9×10^2 and 7.2×10^2 displaced atoms per primary knock-on for Ga and N lattice, respectively [9]. Moreover, large amounts of fast neutrons can induce various defects in GaN lattice such as vacancies, interstitial atoms and defect complexes [10].

It is also possible to homogeneously introduce impurity atoms into semiconducting materials such as GaN by neutrons transmutation doping methods [9], [10]. So, Ge and O impurities are transmuted from Ga and N atoms by (n, γ) reactions.

In this paper, we compare the influence of thermal and fast neutron irradiation on the dc electrical properties of AlGaN/GaN transistors. To our best knowledge, it is the first time that such a study has been presented.

II. Device Fabrication and Experimental Details

AlGaN/GaN HEMTs were processed on epilayers grown by metal organic chemical vapour deposition (MOCVD) on a(0 0 0 1) sapphire substrate (see Fig. 1). It consists of a $5.1\ \mu\mathrm{m}$ GaN non-intentionally doped layer and a 29 nm undoped $\mathrm{Al_{0.25}Ga_{0.75}N}$ layer. Mesa isolation was defined using reactive ion etching (RIE) in a $\mathrm{SiCl_4}$ plasma. Source and drain ohmic contacts were obtained by evaporating Ti/Al/Ni/Au (15 nm/220 nm/40 nm/50 nm) and with annealing at $900^\circ\mathrm{C}$ in a nitrogen atmosphere for 40 s. Pt/Au (10 nm/100 nm) metals were used to form the Schottky contact. The AlGaN/GaN samples were etched in HCl and blown dry with nitrogen before being loaded into the vacuum system for metal deposition. They were in situ exposed to a 150 eV $\mathrm{Ar^+}$ plasma etching for 90 s to deoxidize the AlGaN surface. The gate length was defined by photolithography and is $3\ \mu\mathrm{m}$. The gate width is $50\ \mu\mathrm{m}$. The studied components have a gate-source spacing of $3\ \mu\mathrm{m}$ and a gate-drain distance of $4\ \mu\mathrm{m}$. The devices were not passivated.

The neutron irradiations were performed at EAMEA (Ecole des Applications Militaires de l'EnergieAtomique) by using two different Am-Be sources. One source is dedicated to producing fast neutrons. Another one is enclosed in polyethylene material to slow down the neutrons and then to produce thermalized neutrons. In both cases, neutrons are emitted during the following nuclear process:

$$ {}^{241}_{91}Am \longrightarrow {}^{4}_{2}He + {}^{237}_{89}Np + \gamma \tag{1} $$
$$ {}^{9}_{4}Be + {}^{4}_{2}He \longrightarrow {}^{13}_{6}C \longrightarrow {}^{12}_{6}C + {}^{1}_{0}n + \gamma. \tag{2} $$

These nuclear reactions show that the neutron emission is accompanied by the production of an α particle $({}^{4}_{2}He)$ and γ-rays. It is important to notice that the α particle is absorbed by a steel cylinder surrounding the Am-Be source. The γ-rays emitted during americium disintegration have an energy ranging between 0.06 and 0.96 MeV [11] and the γ-rays induced by the disintegration of ${}^{13}\mathrm{C}$ have an energy of 4.4 MeV [12]. AlGaN/GaN HEMTs were coated with a 1 mm thick sheet of lead during the neutron irradiation in order to absorb γ-rays except those with an energy of 4.4 MeV.

The thermalized neutrons spectrum and the neutrons fluencies have been calculated by a Monte Carlo code named TRIPOLI [13]. These calculations permitted to show that the thermalized neutron spectrum is composed of thermal (33%) and fast neutrons (66%). Moreover, a thermalized neutron fluence rate of 6×10^4 $\mathrm{neutrons.cm^{-2}.s^{-1}}$ was obtained. A fast neutron fluence rate of 1×10^6 $\mathrm{neutrons.cm^{-2}.s^{-1}}$ was also calculated by TRIPOLI.

In this paper, 10 devices have been irradiated by thermalized neutrons and 10 devices have been irradiated by only fast neutrons in order to understand the physical mechanisms induced during each irradiation.

III. Results and Discussions

A. *Influence of Thermalized Neutron Irradiation on Electrical Properties of an AlGaN/GaN Heterojunction*

As the devices have been essentially irradiated by thermal and fast neutrons during a thermalized neutron irradiation, the fluencies of thermalized, thermal and fast neutron irradiations are noticed $\mathrm{D_{thermalized}}$, $\mathrm{D_{thermal}}$ and $\mathrm{D_{fast}}$, respectively, in order to make the understanding of this paper easier.

We have studied the evolution of the drain current $(\mathrm{I_{DS\ max}})$, which is the value of the saturation drain current for a $\mathrm{V_{DS}}$ of 20 V and a $\mathrm{V_{GS}}$ of 1 V, and of the access resistance $(\mathrm{R_{ON}})$ versus the thermalized neutrons fluence to quantify the influence of the thermalized neutron irradiation on the electrical properties of the AlGaN/GaN heterojunction.

$\mathrm{I_{DS\ max}}$ and $\mathrm{R_{ON}}$ have been extracted from $\mathrm{I_{DS}(V_{DS}, V_{GS})}$ characteristics [14] measured before and after thermalized neutron irradiation and $\Delta\mathrm{I_{DS\ max}}$ and $\Delta\mathrm{R_{ON}}$ have been defined by:

$$ \Delta I_{DS\ \max} = \frac{I_{DS\ \max} - I_{DS\ \max\ 0}}{I_{DS\ \max\ 0}} $$
$$ \Delta R_{ON} = \frac{R_{ON} - R_{ON\ 0}}{R_{ON\ 0}} $$

$\mathrm{I_{DS\ max\ 0}}$ and $\mathrm{R_{ON\ 0}}$ have been extracted from $\mathrm{I_{DS}(V_{DS}, V_{GS})}$ characteristics measured before neutron irradiation.

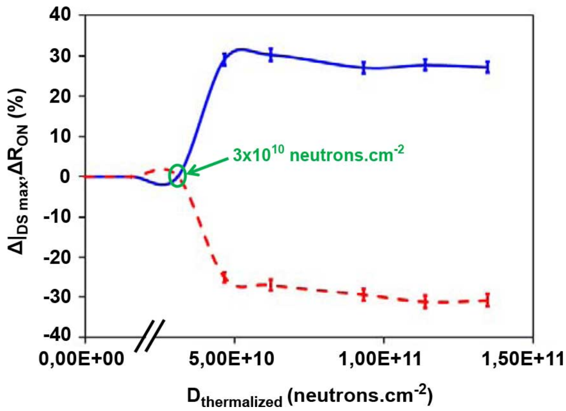

Fig. 2. Evolution of $\Delta I_{DS\ max}$ (solid line) and ΔR_{ON} (dotted line) versus thermalized neutron fluence.

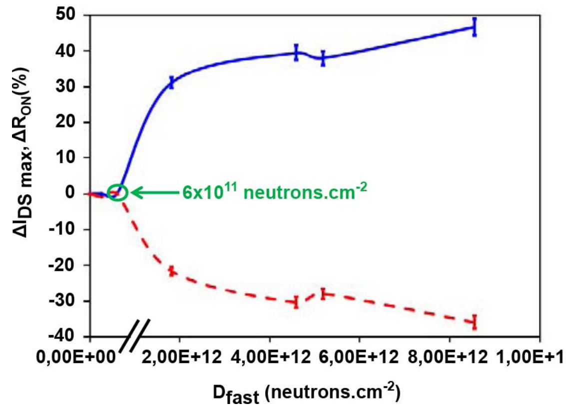

Fig. 4. Evolution of $\Delta I_{DS\ max}$ (solid line) and ΔR_{ON} (dotted line) versus fast neutron fluence.

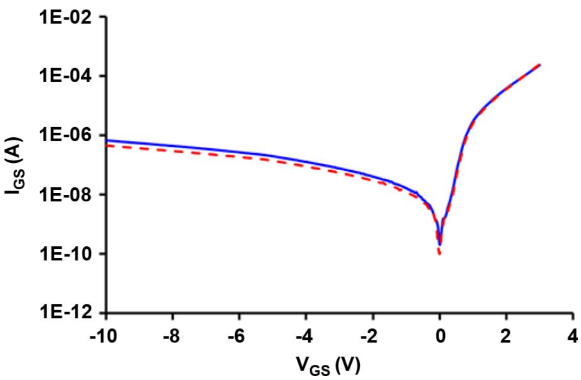

Fig. 3. Evolution of the $I_{GS}(V_{GS})$ characteristics before (solid line) and after a thermalized neutrons radiation fluence of 1.3×10^{11} neutrons.cm^{-2} (dotted line).

The evolution of $\Delta I_{DS\ max}$ and ΔR_{ON} versus thermalized neutron fluence is presented in Fig. 2.

Fig. 2 highlights no evolution of $\Delta I_{DS\ max}$ and ΔR_{ON} when $D_{thermalized}$ changes from 0 up to 3×10^{10} neutrons.cm^{-2}.

We note that $\Delta I_{DS\ max}$ rises up to 30% for a fluence varying from 3×10^{10} up to 4.7×10^{10} neutrons.cm^{-2}. Then $\Delta I_{DS\ max}$ remains quasi-constant when $D_{thermalized}$ increases up to 1.3×10^{11} neutrons.cm^{-2}.

At the same time, ΔR_{ON} decreases down to -25% when $D_{thermalized}$ raises from 3×10^{10} up to 4.7×10^{10} neutrons.cm^{-2} and stays quasi-constant for a higher neutrons radiation fluence.

Fig. 3 shows the electrical characteristics of the Schottky contact before and after a thermalized neutrons radiation fluence of 1.3×10^{11} neutrons.cm^{-2}.

No evolution of the gate current is observed after the thermalized neutron irradiation. In order to study the stability of the Schottky contact, the barrier height (Φ_b) has also been investigated. This parameter has been extracted by fitting the current-voltage curve of the Schottky contact under forward bias to a thermoionic emission model [15] as follows:

$$\phi_b = \frac{K_S.T}{q} ln\left(\frac{AA^*T^2}{l_S}\right)$$

where:

k_B is the Boltzmann's constant;

T is the temperature;

A is the Schottky area;

A^* is the Richardson's constant.

So, Φ_b remains equal to 0.67 eV after a thermalized neutrons radiation fluence of 1.3×10^{11} neutrons.cm^{-2}. This highlights a good stability of the Schottky contact realized in Pt/Au under neutron irradiation for fluence up to 1.3×10^{11} neutrons.cm^{-2}.

The same tendencies for $\Delta I_{DS\ max}$, ΔR_{ON}, Φ_b and for the gate current were observed for the ten devices under study.

So, a30% increase in $I_{DS\ max}$ and a 25% decrease in R_{ON} are induced by using a thermalized neutrons irradiation fluence of 4.7×10^{10} neutrons.cm^{-2}. As mentioned earlier, the thermalized neutron irradiation contains one third of thermal neutrons and two thirds of fast neutrons. Then, in order to explain the evolutions of $I_{DS\ max}$ and R_{ON}, it is imperative to know if it is due to the thermal neutron irradiation and/or to the fast neutron irradiation.

Thus, it is interesting to analyze the impact of fast neutron irradiation on electrical properties of AlGaN/GaN transistors.

B. Influence of Fast Neutron Irradiation on Electrical Properties of an AlGaN/GaN Heterojunction

In order to evaluate the impact of fast neutrons on electrical properties of AlGaN/GaN transistors, 10 components have also been irradiated by only fast neutrons.

Fig. 4 presents the evolution of $I_{DS\ max}$ and ΔR_{ON} versus fast neutron fluence. We can see that $\Delta I_{DS\ max}$ and ΔR_{ON} don't evolve when D_{fast} increases up to 6×10^{11} neutrons.cm^{-2}. However, $\Delta I_{DS\ max}$ increases up to 32% when the neutron fluence varies from 6×10^{11} to 1.8×10^{12} neutrons.cm^{-2}. Then $\Delta I_{DS\ max}$ rises slightly up to 47% for a neutron radiation fluence increasing up to 8.5×10^{12} neutrons.cm^{-2}.

At the same time, ΔR_{ON} decreases starting from 6×10^{11} neutrons.cm^{-2}, and a -22% drop in ΔR_{ON} is noticed when the neutron radiation fluence varies from 6×10^{11} up to 1.8×10^{12} neutrons.cm^{-2}. Then, ΔR_{ON} decreases slightly down to -36% for the neutron radiation fluence increasing up to 8.5×10^{12} $\mathrm{neutrons.cm^{-2}}$.

As in the case of thermalized neutron irradiation, no-evolution of Φ_b and of the gate current were observed after a fast neutron irradiation performed with a fluence of 8.5×10^{12} $\mathrm{neutrons.cm^{-2}}$.

C. Discussion

This study highlights that a thermalized neutron fluence of 4.7×10^{10} $\mathrm{neutrons.cm^{-2}}$ induces a 30% increase in $\Delta I_{DS\ max}$ and a 25% drop in ΔR_{ON}. The results are not in agreement with those reported in the literature [7] because McClory *et al.* have shown a decrease in the drain current and an increase in the gate current after neutron irradiation. We think that this difference is linked to the technological process used to make the devices, the neutron energy (fast or thermalized neutrons) and the neutron fluence used in this paper [7]. In fact, the devices studied by McClory *et al.* have been irradiated with fast neutron fluence of 6×10^{12} $\mathrm{neutrons.cm^{-2}}$ against 1.3×10^{11} $\mathrm{neutrons.cm^{-2}}$ for thermalized neutrons irradiation in our case.

However, Fig. 4 highlights a sharp increase in drain current and a sharp decrease in access resistance for fast neutron fluence changes ranging from 6×10^{11} to 1.8×10^{12} $\mathrm{neutrons.cm^{-2}}$ and a slight evolution of $\Delta I_{DS\ max}$ and ΔR_{ON} has been observed for D_{fast} varying from 1.8×10^{12} up to 8.5×10^{12} $\mathrm{neutrons.cm^{-2}}$. The technological process used to carry out our devices is different from that used by McClory *et al.* [7] and can account for explain these differences. In fact, the thickness of AlGaN/GaN layers, the nature of substrate (SiC) and the gate dimensions are different from those of devices used in our study. However, the metallization of ohmic and gate contacts are not specified in the paper published by McClory *et al.* [7].

As $\Delta I_{DS\ max}$ and ΔR_{ON} do not evolve when AlGaN/GaN heterojunctions were irradiated by fast neutrons by using fluence inferior to 6×10^{11} $\mathrm{neutrons.cm^{-2}}$ (Fig. 4), we can conclude that the increase in $\Delta I_{DS\ max}$ and the drop in ΔR_{ON} observed when devices are irradiated with a $D_{thermalized}$ of 4.7×10^{10} $\mathrm{neutrons.cm^{-2}}$ (Fig. 2) are linked to interactions between thermal neutrons and GaN (or/and AlGaN) material and not to interactions between fast neutrons and GaN (or/and AlGaN) material. In fact, the AlGaN/GaN transistors have been respectively irradiated with $D_{thermal} = 1.6 \times 10^{10}$ $\mathrm{neutrons.cm^{-2}}$ and $D_{fast} = 3.1 \times 10^{10}$ $\mathrm{neutrons.cm^{-2}}$ during this thermalized neutron irradiation.

Moreover, we can affirm that γ-rays (4.4 MeV) emission during the nuclear reactions allowing the production of fast and thermal neutrons have no impact on the electrical properties of AlGaN/GaN heterojunctions because no evolution of $\Delta I_{DS\ max}$ and ΔR_{ON} has been observed during the fast neutron irradiation with a fluence varying up to 6×10^{11} $\mathrm{neutrons.cm^{-2}}$ (Fig. 4).

So, we think that the increase of $I_{DS\ max}$ and the decrease in R_{ON} seen after a thermalized neutrons radiation fluence of 4.7×10^{10} $\mathrm{neutrons.cm^{-2}}$ can be explained by a neutron transmutation doping effect.

In fact neutron irradiation is a useful method for the controlled impurity doped by nuclear reactions and homogeneous defect production because of the strong penetration of neutrons into materials [16], [17].

In the introduction, we mentioned that Ge and O impurities are transmuted from Ga and N atoms, respectively, when GaN layers are irradiated with thermal neutrons [5], [10]. The concentration of the neutron transmuted O atoms is negligibly small because of the very small neutron capture cross section of nitrogen isotopes [9]. Moreover, the quantities of Ti, Al, Ni, Pt, and Au used to carry out the ohmic and Schottky contacts are too small to induce changes in the electrical characteristics of transistors. In these conditions, the impact of the neutron transmuted Ge atoms on electrical properties of AlGaN and/or of GaN layers is predominant.

This phenomenon of transmutation can explain the increase of $I_{DS\ max}$ and the decrease of R_{ON} because Ge is known to act as a donor in GaN or AlGaN layers [10], [18]. Consequently, the thermal neutrons irradiation would permit to realize a n-type doping of the AlGaN and/or of the GaN layers.

In order to prove that the thermalized neutron irradiations induce transmutation reactions of Ge from Ga, we have performed γ-spectrometry measurements to study γ-rays emission, which accompanny the Ge-Ga transmutations produced during the irradiations.

For these reasons, we have compared a gamma spectrum of AlGaN/GaN heterojunction performed after a thermalized neutron irradiation with a fluence of 1.6×10^{10} $\mathrm{neutrons.cm^{-2}}$ (Fig. 5(a)) and a gamma spectrum carried out after a fast neutron irradiation with a fluence of 1.6×10^{10} $\mathrm{neutrons.cm^{-2}}$ (Fig. 5(b)).

Fig. 5(a) shows the γ-rays emitted during the decay of $^{72}_{31}Ga$ and $^{198}_{79}Au$. So, we can affirm that $^{72}_{31}Ga$ and $^{198}_{79}Au$ transmuted to $^{72}_{32}Ge$ and $^{198}_{80}Hg$, respectively, during this thermal neutron irradiation. In fact, the Ga atoms of GaN and AlGaN layers and Au atoms of ohmic and Schottky contacts are transmuted to Ge and Hg atoms after thermalized neutron irradiation. We can add that Al atoms of the AlGaN can also be transmuted to Si atoms and improve the electrical properties of AlGaN/GaN devices because Si atoms is known to act as a n-type dopant. However, it is not possible to highlight the Si-Al transmutation by using γ-spectrometry because no γ-rays are emitted during the transmutation phenomenon. Moreover, we can see the presence of the γ-rays emitted during decay of $^{222}_{86}Rn$ due to the granitic environment.

However, we think that the concentration of Au atoms transmuted to Hg is too small to affect the electrical properties of components as we had to show previously (30% increase in I_{DS} and 25% drop in R_{ON}).As the thermalized and fast neutron irradiation don't change the quality of the Schottky contact (Φ_b stays equal to 0.67 eV after irradiations), we can say that the Hg-Au transmutation has no impact on the ohmic contacts which are solicited during the $I_{GS}(V_{GS})$ characterization. Moreover, the stability of the Schottky contact after thermalized and fast neutron irradiation shows clearly that the Hg-Au transmutation has no impact on the electrical characteristics of the gate.

Fig. 5(b) shows gamma spectrum performed after a fast neutron irradiation with a fluence of 1.6×10^{10} $\mathrm{neutrons.cm^{-2}}$. We can only observe γ-rays emitted during decay of $^{222}_{86}Rn$

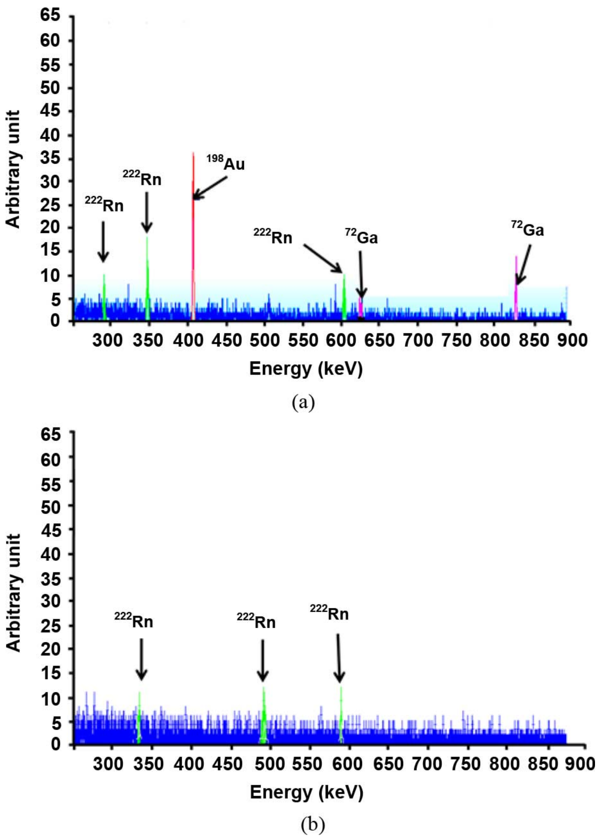

Fig. 5. Gamma spectra of an AlGaN/GaN heterojunction after a thermalized neutron irradiation with a fluence of 1.6×10^{10} $\mathrm{neutrons.cm^{-2}}$ (Fig. 5(a)) and after a fast neutron radiation with a fluence of 1.6×10^{10} $\mathrm{neutrons.cm^{-2}}$ (Fig. 5(b)).

due to the granitic environment. So, we can say that the concentration of the fast neutrons transmuted Ga atoms is inferior to the concentration of the thermalized neutrons transmuted Ga atoms when devices are irradiated with a fluence of 1.7×10^{10} $\mathrm{neutrons.cm^{-2}}$. These results allow to affirm that transmutation are essentially linked to thermal neutrons-Ga interactions and not to fast neutrons-Ga interactions.

However, it is important to notice that AlGaN/GaN heterojunction are irradiated with a fast neutrons fluence of 3.1×10^{10} $\mathrm{neutrons.cm^{-2}}$ during a thermalized neutron irradiation ($\mathrm{D_{thermalized}} = 4.7 \times 10^{10}$ $\mathrm{neutrons.cm^{-2}}$). In fact fast neutrons can cause radiation damage in materials such as vacancies, interstitial atoms and defect complexes [10], [19], [20]. Moreover, fast neutrons emission during the thermalized irradiation of AlGaN/GaN heterojunction can produce displaced atoms such as Ga and N atoms [9]. Besides Kuriyama *et al.* showed that the displacement of N atoms is four larger than Ga atoms, reflecting the lighter weight of N than Ga [9]. Consequently, we can think that the displacement of N atoms is accompanied by the formation of N vacancies, which are known to act as a donor in GaN and AlGaN layers. Moreover, there is a technological process, which consists in creating N vacancies in GaN layer under ohmic contacts by reactive ion etching to decrease the ohmic contact resistivity [21].

However, we can affirm that the improvement of electrical properties shown in Fig. 2 is not linked to N and Ga displacement because Fig. 4 highlights that no evolution of $\Delta\mathrm{I_{DS\ max}}$ and $\Delta\mathrm{R_{ON}}$ is observed when devices are irradiated with fast neutrons fluence inferior to 6×10^{11} $\mathrm{neutrons.cm^{-2}}$. In fact an increase in $\mathrm{I_{DS\ max}}$ and a decrease in $\mathrm{R_{ON}}$ are only observed when devices are irradiated with a fluence superior to 6.10^{11} fast $\mathrm{neutrons.cm^{-2}}$.

We conclude that the evolution of $\Delta\mathrm{I_{DS\ max}}$ and $\Delta\mathrm{R_{ON}}$ highlighted after a thermalized neutrons fluence of 4.7×10^{10} $\mathrm{neutrons.cm^{-2}}$ are essentially linked to transmutation effects induced by the thermal neutrons.

Fig. 4 shows that a fast neutron radiation fluence of 1.8×10^{12} $\mathrm{neutronscm^{-2}}$ implies a 32% raise and a -22% drop in $\Delta\mathrm{I_{DS\ max}}$ and $\Delta\mathrm{R_{ON}}$, respectively. So, this proves that it is necessary to irradiate devices with fast neutron fluence higher than thermal neutron fluence to improve electrical properties of AlGaN/GaN heterojunction. We think this is due to the fact that the fast neutron capture cross section of Ga (0.016 barn/atom) is inferior to the thermal neutron capture cross section of Ga (2.8 barn/atom).

We think that these evolutions are induced either by transmutation effects or by displacement of N atoms.

Moreover, it is known that fast neutron irradiations cause damage in the material [10], [19], [20]. We think that fast neutrons radiation fluence superior to 6×10^{11} $\mathrm{neutron.cm^{-2}}$ induces displacement of N atoms and consequently the formation of N vacancies, which would explain the improvement of the drain current and the access resistance shown in Fig. 4.

We can add that it is also possible that fast neutrons radiation changes the strain state of layer [22] and improve the piezoelectric field, which would imply an increase in carrier density in the channel of the component.

IV. Conclusion

We have shown that it is possible to increase the drain current and decrease the access resistance by irradiating AlGaN/GaN structures with thermalized neutrons or with fast neutrons. However, a lower thermalized neutrons fluence than fast neutrons fluence is necessary to induce a rise of $\mathrm{I_{DS\ max}}$ and a drop of $\mathrm{R_{ON}}$. We have also highlighted that these evolutions are essentially explained by a transmutation effect when AlGaN/GaN heterojunctions are irradiated by thermalized neutrons or by fast neutrons. However, we also think that N vacancies and/or a change in the strain state of the layers can also contribute to the improvement of dc electrical performances of AlGaN/GaN transistors during the fast neutrons irradiation. Moreover, the Schottky contact remains stable up to $\mathrm{D_{thermalyzed}}$ of 1.3×10^{11} $\mathrm{neutrons.cm^{-2}}$ and up to $\mathrm{D_{fast}}$ of 8.5×10^{12} $\mathrm{neutrons.cm^{-2}}$.

References

[1] Y. Ando, Y. Okamoto, H. Miyamoto, T. Inoue, and M. Kuzuhara, "10 W/mm AlGaN-GaN HFET with a field modulating plate," *IEEE Electron. Device Lett.*, vol. 24, no. 5, pp. 289–291, May 2003.

[2] Y. F. Wu, A. Saxler, M. Moore, P. Smith, S. Sheppard, P. M. Chavarkar, T. Wisleder, U. K. Mishra, and P. Parikh, "30 W/mm GaN HEMTs by field plate optimization," *IEEE Electron. Device Lett.*, vol. 25, no. 3, pp. 117–119, Mar. 2004.

[3] L. F. Eastman, V. Tilak, J. Smart, B. M. Green, E. M. Chumbes, R. Dimitrov, H. Kim, O. S. Ambacher, N. Weimann, T. Prunty, M. Murphy, W. J. Schaff, and J. R. Shealy, "Undoped AlGaN/GaN HEMTs for microwave power amplification," *IEEE Trans. Electron Devices*, vol. 48, no. 3, pp. 479–485, Mar. 2001.

[4] A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, A. V. Markov, S. J. Pearton, N. G. Kolin, D. I. Merkurisov, V. M. Boiko, M. Skowronski, and H. I. Lee, "Neutron irradiation effects in AlGaN/GaN heterojunctions," *Phys. B: Cond. Matter.*, vol. 376–377, pp. 523–526, Apr. 2006.

[5] M. L. Zhang, X. L. Wang, H. L. Xiao, C. M. Wang, J. X. Ran, and G. X. Hu, "Neutron irradiation effect in two-dimensional electron gas of AlGaN/GaN heterostructures," *Chin. Phys. Lett.*, vol. 25, no. 3, pp. 1045–1048, Mar. 2008.

[6] A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, A. V. Markov, S. J. Pearton, N. G. Kolin, D. I. Merkurisov, and V. M. Boiko, "Neutron irradiation effects on electrical properties and deep-level spectra in undoped n-AlGaN/GaN heterostructures," *J. Appl. Phys.*, vol. 98, no. 3, pp. 033529.1–033529.6, Aug. 2005.

[7] J. W. McClory and J. C. Petrosky, "Temperature dependent electrical characteristics of neutron irradiated AlGaN/GaN HFETs," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, pp. 1969–1974, Dec. 2007.

[8] J. C. Petrosky, J. W. McClory, T. E. Gray, and T. A. Uhlman, "Trap assisted tunneling induced currents in neutron irradiated AlGaN/GaN HFETs," *IEEE Trans. Nucl. Sci.*, vol. 56, no. 5, pp. 2905–2909, Oct. 2009.

[9] K. Kuriyama, Y. Mizuki, H. Sano, A. Onoue, K. Kushida, M. Okada, M. Hasegawa, I. Sakamoto, and A. Kinomura, "Lattice disorder in neutron irradiated GaN: Nuclear reaction analysis and Rutherford back scattering studies," *Nucl. Instrum. Methods Phys. Res. B*, vol. 249, no. 1–2, pp. 132–135, Aug. 2006.

[10] K. Kuriyama, T. Tokumasu, J. Takahashi, H. Kondo, and O. Okada, "Lattice distortions and the transmuted-Ge related luminescence in neutron-transmutation-doped GaN," *Appl. Phys. Lett.*, vol. 80, no. 18, pp. 3328–3330, May 2002.

[11] G. Pfennig, H. Klewe-Nebenius, and W. Seelmann-Eggebert*, Chart of the Nuclides*. Germany: Druckhaus Haberbeck GmbH.

[12] H. R. Vega-Carillo, E. Manzanares-Acuna, A. M. Becerra-Ferreiro, and A. Carillo-Nunez, "Neutron and gamma-ray spectra of $^{239}\mathrm{PuBe}$ and $^{241}\mathrm{AmBe}$," *Appl. Rad. Isotopes*, vol. 57, no. 2, pp. 167–170, Aug. 2002.

[13] Tripoli-4, Monte Carlo Transport Code for Neutral Particles Version 4 User's Manual 2008, CEA-R-6170.

[14] F. Berthet, Y. Guhel, H. Gualous, B. Boudart, J. L. Trolet, M. Piccione, V. Sbrugnera, B. Grimbert, and C. Gaquiere, "Characterization and analysis of electrical trap related effects on the reliability of AlGaN/GaN HEMTs," *Solid-State Electron.*, vol. 72, pp. 15–21, Jun. 2012.

[15] G. Wenping, C. Chi, D. Huantao, H. Yue, Z. Jincheng, W. Chong, F. Qian, and M. Xiaohua, "$^{60}\mathrm{Co}$ γ-rays irradiation effect in DC performances of AlGaN/GaN high electron mobility transistor's," *J. Semicond.*, vol. 30, no. 4, pp. 0440021–0440025, Apr. 2009.

[16] M. Satoh, K. Kuriyama, and T. Kawakubo, "Depth uniformity of electrical properties and doping limitation in neutron transmutation doped semi-insulating GaAs," *J. Appl. Phys.*, vol. 67, no. 7, pp. 3542–3544, Apr. 1990.

[17] B. Boudart, B. Mari, B. Prevot, and C. Schwab, "Efficiency of neutron transmutation doping of InP investigated by optical and electrical methods," *Nucl. Instrum. Methods Phys. Res. Section B: Beam Interactions Mater. Atoms*, vol. 63, no. 1–2, pp. 101–105, Jan. 1992.

[18] P. R. Hageman, W. J. Schaff, J. Janinski, and Z. Liliental-Weber, "N-type doping of wurtzite GaN with germanium grown with plasma-assisted molecular beam epitaxy," *J. Crystal Growth*, vol. 267, no. 1–2, pp. 123–128, Jun. 2004.

[19] R. N. Thomas, T. T. Braggins, H. M. Hobgood, and W. J. Takei, "Compensation of residual boron impurities in extrinsic indium doped silicon by neutron transmutation of silicon," *J. Appl. Phys.*, vol. 49, no. 5, pp. 2811–2820, May 1978.

[20] J. J. Rome, W. C. Mitchel, G. J. Brown, D. W. Fisher, M. C. Ohmer, and T. L. Peterson, "X-center formation by neutron irradiation of Ga-doped float zone silicon," *Appl. Phys. Lett.*, vol. 41, no. 3, pp. 254–255, Aug. 1982.

[21] J. Würfl, V. Abrosimova, J. Hilsenbeck, E. Nebauer, W. Rieger, and G. Tränkle, "Reliability considerations of III-nitride microelectronics devices," *Microelectron. Rel.*, vol. 39, no. 12, pp. 1737–1757, Dec. 1999.

[22] J. G. Marques, K. Lorenz, N. Franco, and E. Alves, "Defect production in neutron irradiated GaN," *Nucl. Instrum. Methods Phys. Res. B*, vol. 249, no. 1–2, pp. 358–361, Aug. 2006.