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Recessed and P-GaN Regrowth Gate Development for Normally-off AlGaN/GaN HEMTs

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***Abstract*—A new normally-off AlGaN/GaN HEMT structure is proposed. The regrowth of a P-GaN layer on the AlGaN/GaN heterostructure after the gate recess allows the achievement of the enhancement mode. A shift in the threshold voltage to positive values has been proved through simulation results. A precise control of the etch depth for the gate recess is detailed.**

***Keywords*—HEMT; normally-off; AlGaN/GaN; gate recess; RIE; P-GaN regrowth.**

I. INTRODUCTION

AlGaN/GaN high-electron mobility transistors (HEMTs) have attracted worldwide attention in power electronics as candidates for next-generation of high-speed switching devices. Thanks to the large electric field of GaN and the high carrier mobility and density in the two-dimensional electron gas (2DEG), AlGaN/GaN HEMTs can achieve high breakdown voltage and realize ultrahigh power density operation with low power losses.

While most of the demonstrated AlGaN/GaN HEMTs are inherently normally-on with a negative gate threshold voltage, normally-off mode is strongly demanded to fulfill the requirements of power electronics applications; normally-off devices are inherently secure and suitable for energy converters requiring specifically high system reliability. Several approaches, each with its own limitations, have been proposed to convert the inherent depletion mode (normally-on) into an enhancement one (normally-off). Fluorine plasma ion implantation [1], oxygen treatment [2], gate injection transistor (GIT) [3] and P-GaN gate [4] are the most developed ones. In this paper a structure that combines two approaches (recessed and P-GaN regrowth gate) is presented. The use of a P-GaN layer on the AlGaN/GaN heterostructure under the gate contact region lifts up the band diagram, which causes the depletion of the 2DEG channel, even in the absence of external bias. First, the simulated performance of the new device will be presented, then an overview of the technological process mandatory to realize such a device will be proposed, with a particular focus on the gate recess step.

II. THE SIMULATED STRUCTURE

Numerical simulations were performed with Sentaurus TCAD tools in order to have an insight of the HEMT parameter sensitivity. The designed structure has source, drain and gate contact lengths of 1 µm, a gate-source distance of 2 µm and a gate-drain distance of 15 µm. A gate field plate of 3 µm is added at drain side. Contrary to other studies [5] [6], the deep ionization energy of the Mg dopant is not considered, which means that this region presents an "equivalent" uniform doping profile. Comparative simulations (not presented) with the use of the "incomplete ionization" model present similar results in terms of threshold voltage. Two cases were analyzed: the one with the gate metal directly on top of the P-GaN region, and the other with an insulator between them (Fig. 1).

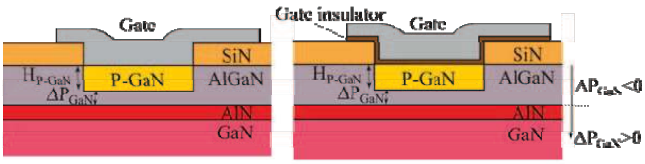

Fig. 1. Gate detail of the proposed structure with metal on P-GaN (left) and with gate insulator on top of P-GaN (right)

First simulations were performed on structures with metal on P-GaN. Band diagram through the gate at 0 V for different AlGaN thicknesses below the gate is presented in

Fig. 2. The etched AlGaN effect can be seen on the conduction band profile, especially at GaN side. Negative ΔP_{GaN} values means that the remaining AlGaN layer under the gate provides higher polarization charge to deplete, that finnaly results to lower threshold voltage.

Simulation results of the threshold voltage variations as a function of the P-GaN doping are represented in Fig. 3. When considering ohmic contact, no depletion appears on P-GaN, that can be confirmed by the absence of band bending on

Fig. 2, so the threshold voltage is independent on P-GaN doping concentration. On the contrary, the Schottky contact puts the energy bands downward for lower values of doping concentration, while only high doping values will pin the Fermi

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level close to the valence band. Therefore, the threshold voltage variation is related to the depletion thickness on P-GaN.

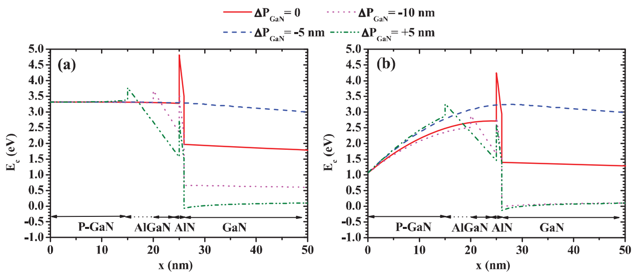

Fig. 2. Conduction band energy profile through the gate for different ΔP_{GaN} values for ohmic (a) and Schottky (b) gate contact.

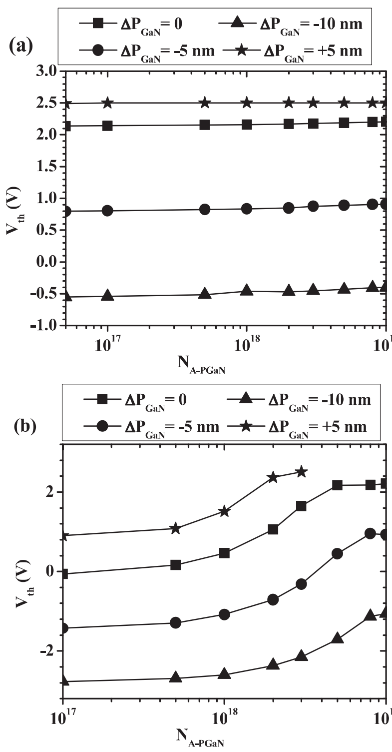

Fig. 3. Threshold voltage as a function of P-GaN doping concentration for different ΔP_{GaN} values when the gate contact is defined ohmic (a) and Schottky (b).

For the analysis of the structure with a gate insulator, the material used as insulator as well as its thickness have to be considered. Materials such as SiO_2 or Al_2O_3 are promising due to their higher bandgap and electron affinity [7], which means an increase in the conduction band continuity with the P-GaN. However, the lower relative permittivity of SiO_2 is not favourable in terms of electrical characteristics since it gives lower transconductance as represented in Fig. 4. Moreover, it has been demonstrated that SiO_2 induces high density of surface states with GaN [8].

Threshold voltage variations with P-GaN doping concentration for different insulator materials and thicknesses are presented in Fig. 5. Interface states density has been inserted, based on extracted values for structures with the Si_3N_4 layer deposited on P-GaN by LPCVD. These values are expected to change with the insulator material and its deposition method.

Results from structures with insulator show similar trends that previously observed. The additional layer of dielectric absorbs more or less electric field when a gate voltage is applied, depending on its thickness and permittivity, enhancing by the way the threshold voltage variation with doping concentration, which means that the threshold voltage presents stronger voltage variations with P-GaN doping. If high P-GaN doping concentration can be demonstrated, high positive threshold voltage is achievable.

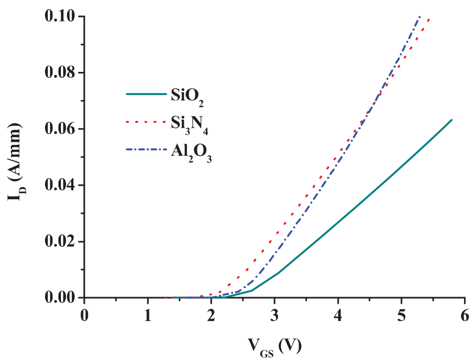

Fig. 4. Transfer characteristics I_D (V_{GS}) of HEMT with different gate insulators of 30 nm thick.

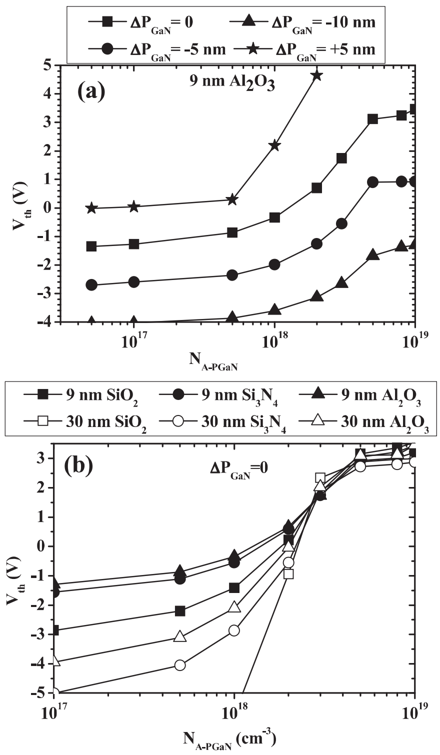

Fig. 5. Threshold voltage as a function of doping concentration for different parameters: (a) P-GaN distance(ΔP_{GaN}) from AlN surface for 9 nm of Al_2O_3 and (b) different insulator materials and thicknesses.

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III. GATE RECESS PROCESS

A fabrication process of the presented device was conducted in order to validate the simulation results previously detailed. The AlGaN/GaN HEMT layers were grown by metal organic chemical vapor deposition (MOCVD) on Si: the epilayer stacking is composed of an alternation of AlN/GaN layers, followed by a 1.5 µm GaN, 1.5 nm AlN interface enhancement layer, a 25 nm $Al_{0,3}GaN_{0,7}$ layer and a 10 nm SiN cap layer.

Before the gate recess, 50 nm of Si_3N_4 and 100 nm of SiO_2 were deposited on the epitaxial layers, by LPCVD and ICPECVD respectively (Fig. 6.a) The role of Si_3N_4 is to conserve the 2DEG density and the SiO_2 one is to prevent the growth of the P-GaN outside the gate region. The gate is then opened through the etching of three materials: SiO_2 and Si_3N_4 were both removed by CHF_3/O_2 ICP plasma and AlGaN by Cl_2 RIE dry etching (Fig. 6.b). This step is pursued by localized MBE epitaxy of a P-GaN layer into the gate region (Fig. 6.c). The SiO_2 masking layer is removed thereafter by wet etching (Fig. 6.d).

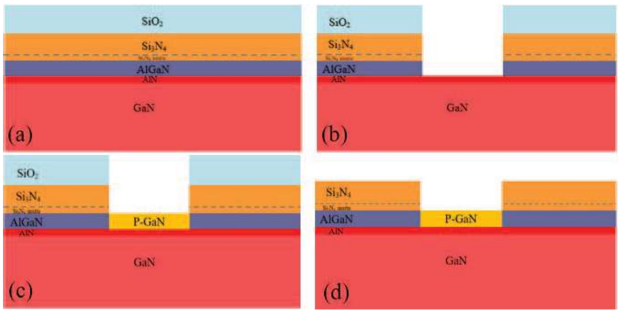

Fig. 6. Schematic process flow of the localized regrowth of p-GaN on the gate region. (a) Succession of the epitaxial layers on the Si substrate; (b) gate recess by dry plasma etching (CHF_3/O_2 for Si_3N_4 and SiO_2, Cl_2 for AlGaN); (c) P-GaN regrowth by MBE with a Mg doping; (d) SiO_2 removal by wet etching.

A. *AlGaN etching*

For the gate recess, inductively coupled plasma or reactive ion etching (ICP-RIE) are the most used techniques owing to their anisotropy etching and efficiency. However, several requirements must be fulfilled when using these techniques such as a smooth surface morphology and a low damage. As mentioned before, a normally-off P-GaN technology requires the use of a thin AlGaN barrier layer (25 nm), therefore the etching rate has to be well-controlled in order to preserve the 2DEG properties. Selectivity is a very important factor in mastering etching rate: it depends on several parameters such as gas chemistry, chamber pressure and temperature. To the best of our knowledge, there is no selective recipe for AlGaN etching and the etch rate strongly depends on plasma conditions. The majority of AlGaN etching processes are based on chlorine as a principal etching agent: the chlorine-containing reactant may be boron trichloride (BCl_3), chlorine (Cl_2), or a mixture of the two gases [9].

In the present work, a Cl_2-based etching was carried out in a RIE plasma etch system for the AlGaN gate recess. The etching conditions were the same as reported by D. Buttari *et al.* [10]: RF power = 60 W, pressure = 5 mTorr and Cl_2 flow = 10 sccm. The wafer was patterned using ECI 3012 photoresist of 1.1 µm thick. The removal of the photoresist mask, after etching, was performed by acetone and isopropanol (IPA), followed by DI water and O_2 plasma (800 W). However, further cleaning was necessary for removing the photoresist post-etch residues remaining on the AlGaN layer: it will be discussed later. Etch depths were measured by transmission electron microscopy (TEM) and determined to be about 6 nm, 19 nm and 21 nm for 25 s, 35 s and 45 s etching times respectively. A FIB sectional view of the gate after etching is presented in Fig. 7 for 35 s AlGaN etching.

The use of a medium RIE power (< 100 W) and the consequent slow etch rate allowed an accurate control of AlGaN thinning. Times lower than 25 s have not been tested because of the eventual presence of a thin surface oxide layer formed before the etch, that can give rise to a dead time by inhibiting etch at the beginning [11]. Above 45 s, the AlGaN is completely etched as well as the underlying layers, AlN and part of GaN.

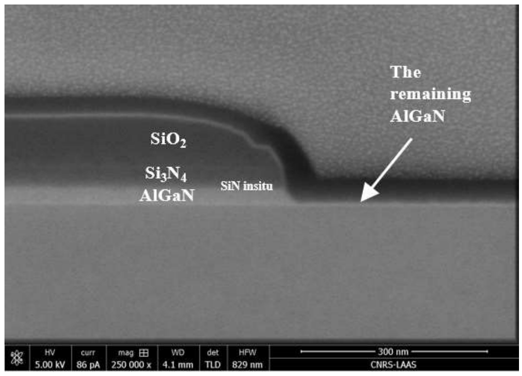

Fig. 7. Picture of FIB cut after the gate recess for RIE AlGaN etching of 35 s.

B. *Surface roughness*

The root means square roughness RMS measured by AFM on a 2 x 2 µm2 windows before and after etching are respectively 0.43 nm and 1.22 nm as shown in Fig. 8. The AlGaN surface observed after a partial etching of 25 s exhibited a RMS three times higher than the non-etched AlGaN one. It is very difficult to compare these values to those of literature because the roughness after etching depends on the as-grown surface roughness and the etching parameters. However, the obtained values remain in the range of values reported in literature [12].

It has been proved that the RMS roughness of the etched AlGaN can be strongly affected by oxidation during plasma etching; the in-situ produced aluminum oxides may provide a self-mask effect [13]. Given that the bond energy of Al-O (21.2 eV/atom) is higher than that of Al-N (11.52 eV) and Ga-N (8.92 eV), AlGaN etch would be limited by the formation of the aluminum oxide. Therefore, the non-uniformity of the aluminum oxide distribution will cause roughness on the etched surface. The addition of an appropriate quantity of BCl_3 to the plasma mixture could help to improve the smoothness of the etched surface. Indeed, BCl_3 reacts with oxygen to form some BCl_xO_y gases which could facilitate the removal of the oxygen remaining into the chamber [14].

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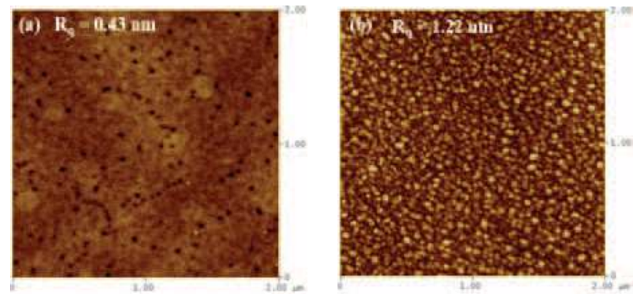

Fig. 8. AFM surface images of the AlGaN (a) before etching, (b) after Cl_2-RIE etching for 25 s: RF power = 60 W, pressure = 5 mTorr and Cl_2 flow = 10 sccm.

C. Post-etch residues

After the resist removal, we observed some residues on the etched surface that were very difficult to eliminate by conventional wet stripping methods. The SEM image in Fig. 9.a shows a veil residue on the etched region. These residual impurities are inherent by-products of the Cl_2-based etch process. They are probably formed by a mixture of species stemming from the plasma ions, the photo-resist mask and the etched materials (SiO_2, Si_3N_4 and AlGaN), which prevents dissolution by solvents. Several experiments conducted to remove these tenacious post-etch residues by common chemical strippers were ineffective [15]. The selected solution consists of UV insolation of the wafer followed by a developing step. The efficiency of the after-etching cleaning can be observed in Fig. 9.b.

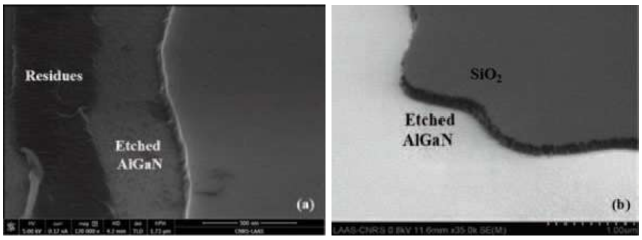

Fig. 9. SEM image showing (a) post-etch residues after the resist removal by acetone, isopropanol and DI water followed by O_2 plasma (5 min, 800 W); (b) the removal of the post-etch residues by UV insolation and development after etching.

IV. Conclusion

In this work, a new design of a normally-off HEMT was proposed. The introduction of a P-GaN layer on the AlGaN/GaN heterostructure under the gate contact allows the normally-off functionality. The simulations were carried out in two cases: metal on P-GaN (ohmic and Schottky) and gate with insulator for different recess depths and P-GaN doping concentrations. High threshold voltages can be achieved by reducing the thickness of the remaining AlGaN. With the ohmic contact, the threshold voltage is independent on P-GaN doping concentration, contrary to the Schottky one. With the gate insulator structure, the electrical performance depends on the type of insulator and its thickness. Then, a focus on the gate recess process, mandatory for the realization of such devices, was also detailed in this work. A precise AlGaN etching was achieved by adjusting Cl_2-RIE etching parameters. The roughness surface after etching was three times higher than the non-etched one but remains acceptable for a RIE mode. Some post-etch residues were found on the etched AlGaN surface and were removed by UV insolating and developing steps. The work of realization oh the whole fabrication process of the AlGaN /GaN HEMT is underway in order to demonstrate the normally-off behavior of such a device.

Acknowledgment

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