Normally-Off AlGaN/GaN HEMT using fluorine implantation below the channel

Saleem HAMADY[1,2,4], Frédéric MORANCHO[1,3],Bilal BEYDOUN[4], Patrick AUSTIN[1,3],Mathieu GAVELLE[5]
[1]CNRS, LAAS, 7 avenue du colonel Roche, F-31400 Toulouse, France
[2]Univ de Toulouse, LAAS, F-31400 Toulouse, France
[3]Univ de Toulouse, UPS, LAAS, F-31400 Toulouse, France
[4]GET/LPE, Lebanese University, Hadath campus, Beirut, Lebanon
[5]CEA Tech Midi-Pyrénées, 2 avenue Édouard Belin F31055 Toulouse Cedex 4, France
E-Mail: shamady@laas.fr, morancho@laas.fr, bilbey@ul.edu.lb,austin@laas.fr, mathieu.gavelle@cea.fr

RESUME - AlGaN/GaN HEMTs are very promising candidates for high frequency applications with high power and low noise. Unfortunately, while switching applications strongly demand normally-off operation, conventional HEMTs are normally-on. For the sake of achieving normally-off HEMTs, several structures have been proposed. One of the major normally-off HEMTs uses fluorine implantation in the AlGaN layer. We suggest in this work the implantation of fluorine ions under the AlGaN/GaN interface only below the gate electrode rather than implanting in the AlGaN layer. Simulation results show that the proposed method is capable of achieving normally-off operation and more effective when it comes to the fluorine concentration required to obtain the desired threshold voltage. Neither the vertical breakdown voltage, nor the off-state current are affectedby this approach.

Keywords— TCAD simulation, normally-off, Gallium Nitride (GaN), High electron mobility transistor (HEMT), fluorine implantation

1. INTRODUCTION

The High Electron Mobility Transistor (HEMT) is a field effect transistor in which two layers of different bandgaps and polarization fields are grown upon oneanother. As a consequence of the discontinuity in the polarization field, surface charges at the heterointerface are created. If the induced charge is positive, electrons will tend to compensate the induced charge resulting in the formation of a two dimensional electron gas (2DEG)[1]. Thanks to the GaN properties and the HEMT's topology, AlGaN/GaN HEMTs are now promising devices for high frequency applications with high power and low noise, such as microwave and millimeter wave communications, imaging and radars [2].

In the conventional HEMT, the energy levels of the triangular quantum well, formed in the GaN layer below the AlGaN/GaN interface, are below the Fermi level at equilibrium. This will make the channel populated with electrons at zero gate voltage, hence making the HEMT normally-on. However, for power switching applications, normally-off operation is strongly required [3]. In order to achieve normally-off operation, the energy levels must be lifted above the Fermi level. Several structures have been proposed for the realization of normally-off AlGaN/GaN HEMT such as recessed gate structures [4], fluorine ion treatment [5], pn junction gate structures [6], thin AlGaN barrier[7], AlN/GaN structure [8] and conventional HEMT with InGaN cap layer [9]. In the normally-off HEMT reported in [5], fluorine ions are implanted in the barrier layer (AlGaN layer). When this approach is used, small amount of fluorine ions penetrate into the channel formed at the AlGaN/GaN interface, presenting themselves as impurities that lead to mobility degradation [10]. In this paper, we propose to implement the ions below the channel (in the GaN layer) under the AlGaN/GaN interface, and that only below the gate electrode. To obtain this structure, the following can be done: after growing the buffer and GaN layers, fluorine ions will be implanted. Then the channel layer of GaN (15 nm) will be introduced, and above all comes the AlGaN layer (barrier layer). This way, no scattering will occur between the 2DEG and the fluorine ions since the fluorine ions are below the channel region.

2. SIMULATION STRATEGY

ATLAS, a physically-based TCAD simulation tool from Silvaco, is used to analyze the new HEMT structure. Physical models of the simulator are based on Shockley-Read Hall recombination, Fermi-Dirac statistics and field-dependent mobility [11]. The simulator is calibrated by using real parameters of a normally-on HEMT device, as shown in figure 1.

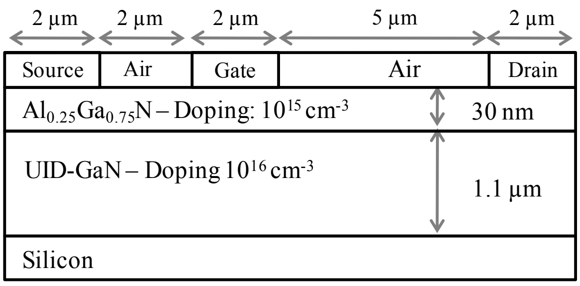

Fig. 1. Schematic cross-section of the normally-on HEMT structure used for the calibration of the TCAD simulations.

In figure 2, the simulation results are presented and compared with the experimental transfer characteristics I_d (V_{gs}). A good match is observed for the threshold voltage (V_{th}) and the transconductance (g_m). During calibration, the energy and the concentration of the acceptor traps as well as the density of the 2DEG were tuned. In Table 1, some of the parameters used for the simulation are illustrated.

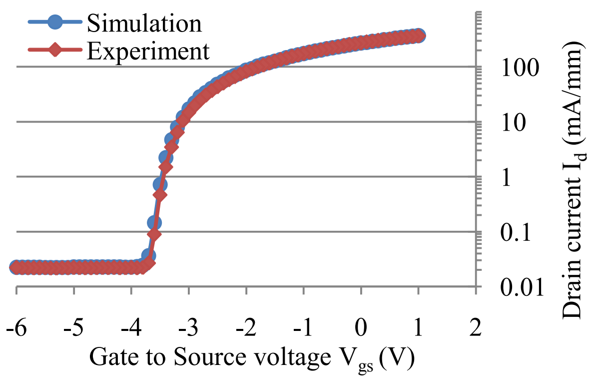

Fig. 2. Comparison of experimental and simulated $I_d(V_{gs})$ transfer characteristics showing a clear match for the threshold voltage and transconductance.

Table 1: HEMT simulation parameters

Density of acceptor traps	10^{17}cm^{-3}
Energy of acceptor traps	0.41 eV
Interfacial charge density	k(P_{GaN} - P_{AlGaN}) / q cm^{-2}
Fitting Parameter k	0.61

To simulate the effect of the implanted fluorine ions, negative charge was added inside the GaN (or AlGaN) layer. To do that using ATLAS, the GaN (or AlGaN) layer was split into two layers. This will generate an interface (GaN/GaN or AlGaN/AlGaN homo-interface) inside the layer. At this interface, a fixed negative charge is added. Although the profile of the fluorine ions concentration, resulting from this approach, differs from the profile experimentally obtained, its effect on the transfer characteristics can be imitated by varying the concentration of negative charge at the interface.

3. SIMULATION RESULTS

3.1. Fluorine implantation in AlGaN layer

Figure 3 shows the transfer characteristics of the conventional normally-on HEMT of figure 1 (“Null”) and HEMTs with fluorine implanted in AlGaN (figure 4) at various concentrations (from 4 × 10^{12} to 1.4 × 10^{13} cm^{-2}). The distance between the fluorine ions and the AlGaN/GaN interface is taken 15 nm. It is clear that, at a certain fluorine concentration (1.4 × 10^{13} cm^{-2}), this technique is capable of shifting the threshold voltage to a positive value (0.5 V), making the HEMT normally-off.

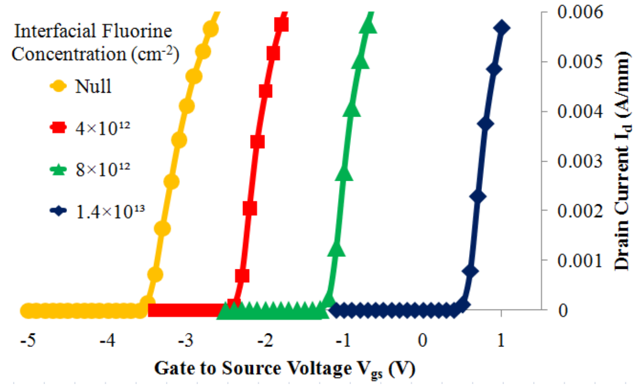

Fig. 3. I_d (V_{gs}) transfer characteristics of the conventional normally-on HEMT and HEMTs with fluorine implanted in AGaN at various concentration.

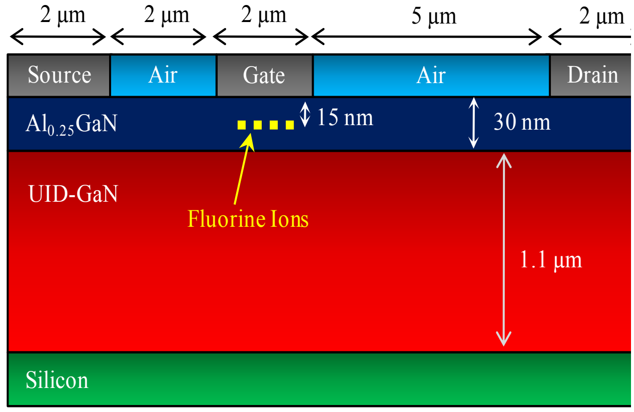

Fig. 4. Schematic cross-section of the simulated HEMT with fluorine implanted in the AlGaN layer.

3.2. Fluorine implantation in the GaN layer

Figure 5 shows the transfer characteristics of the conventional normally-on HEMT of figure 1(“Null”) and HEMTs with fluorine implanted in the GaN layer (Figure 6) at different concentrations (from 4 × 10^{12} to 8 × 10^{12} cm^{-2}). The distance between the fluorine ions and the AlGaN/GaN interface is also

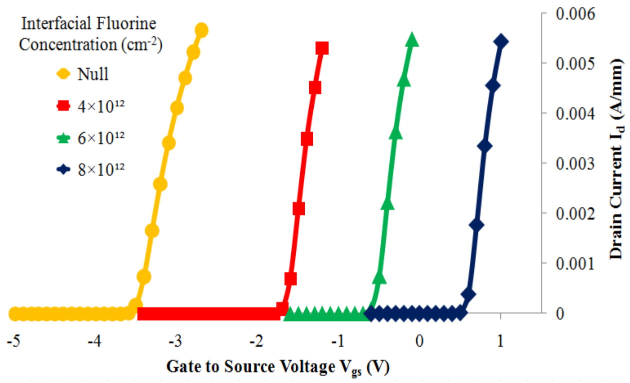

Fig. 5. I_d (V_{gs}) transfer characteristics of the conventional normally-on HEMT and HEMT with fluorine implanted in GaN at various concentration.

taken to be 15 nm. As the fluorine concentration increases, the threshold voltage increases to positive values, confirming that our technique is also capable of achieving normally-off HEMT.

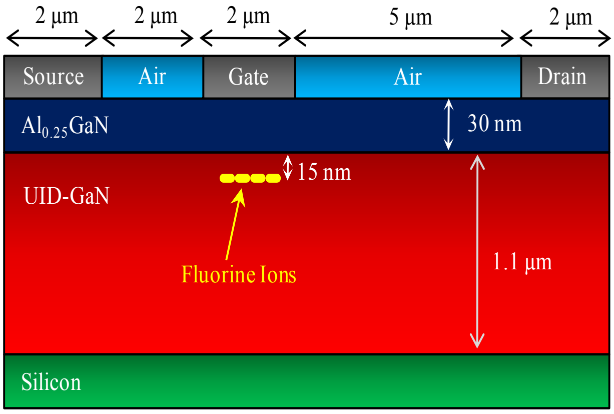

Fig. 6. Schematic cross-section of the simulated HEMT with fluorine implanted in the GaN layer

It can be seen from figures 3 and 5 that although the same threshold voltage (0.5 V) was achieved after implantation in both cases, the fluorine concentration required to achieve the desired threshold voltage is lower ($8\times10^{12} < 14\times10^{12}$) when implantation is performed in the GaN layer rather than in the AlGaN layer, making our proposed technique more efficient.

4. Energy Band Diagram

To further explore the consequences of the two different techniques, the band diagrams for the two structures are shown in figure 7. It can be concluded from this figure that the implantation in GaN is more effective: since HEMTs attain Schottky gates, the conduction band at the top of the AlGaN layer is pinned at a fixed energy equals to the Schottky barrier. If it was not for that pinning, the conduction band in AlGaN would have risen higher when fluorine is implanted, causing a higher shift in thethreshold voltage. Moreover, it can be noted, from the band diagram, that the confinement of the2DEG under the gate is superior in the case of Fluorine implanted in GaN (see zoom in Figure 7).

5. Breakdown and Off-State Current

To examine the off-state current and the breakdown voltage, the structure shown in figure 6 was studied. However, due to convergence problems at high voltages in the normally-off HEMT with high fluorine concentrations, a smaller x-mole fraction of 0.15 was used instead. In this case, a smaller fluorine concentration of 4.2×10^{12} cm^{-2} is needed to achieve normally-off operation with a threshold voltage of 0.5 V. The same HEMT (x-mole fraction of 0.15) with no fluorine implantation attains a threshold voltage of -2 V.

Figure 8 shows the variation of the drain current with the applied drain to source voltage $I_d(V_{ds})$. In order to study the two HEMTs in the off-state, i.e. below their threshold voltage, the applied gate to source voltage is: $V_{gs} = V_{th} - 1$ V. It is clear that neither the vertical breakdown voltage, nor the off-state current are affected by the implanted fluorine ions. A breakdown voltage of 280 V was obtained in both cases.

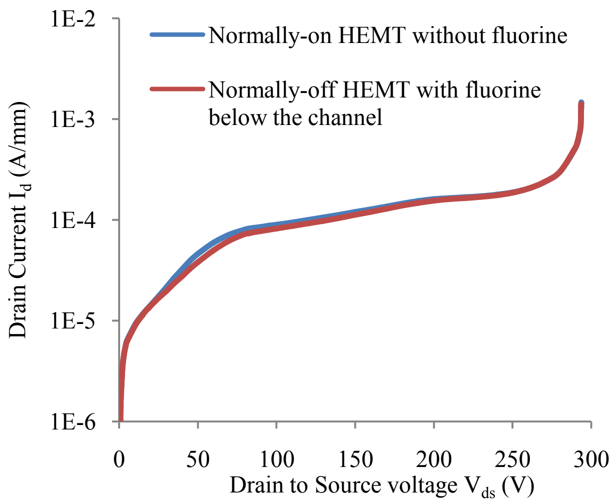

Fig. 8. Simulated $I_d(V_{ds})$ characteristics in the off-state, showing the off-state current and the breakdown voltage of the normally-on HEMT and the normally-off HEMT with fluorine implantation below the channel.

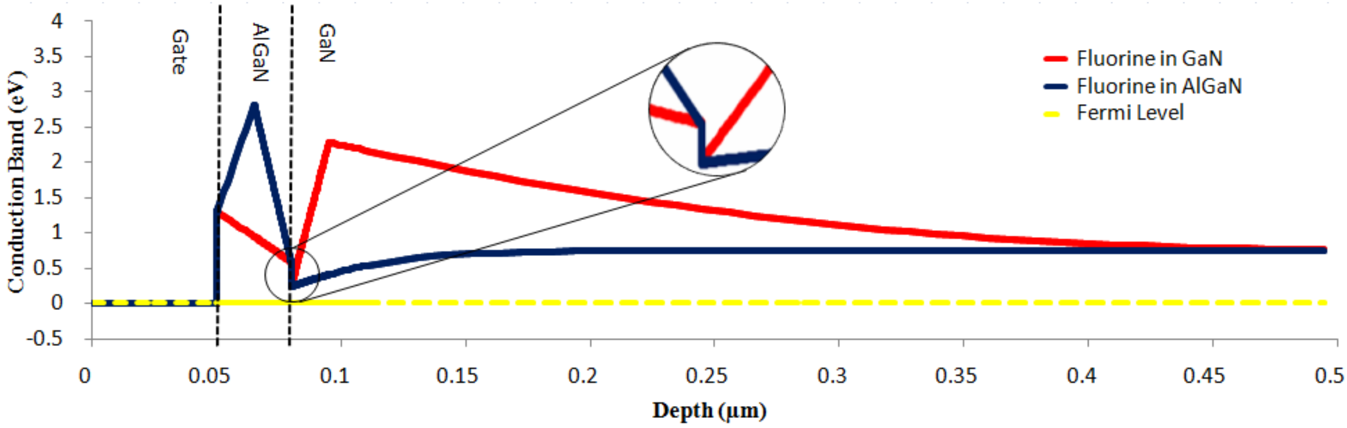

Fig. 7: Band diagrams of HEMT with fluorine implanted in AlGaN at concentration $1.4\times10^{13}cm^{-2}$ and HEMT with fluorine in GaN at concentration $8\times10^{12}cm^{-2}$; both HEMTs attain a threshold voltage of 0.5 V.

6. CONCLUSION

In this work, for the sake of obtaining a normally-off HEMT, we suggest the implantation of fluorine ions in the GaN layer, under the AlGaN/GaN interface only below the gate electrode, rather than the implantation in the AlGaN layer as previously proposed in other papers. Using numerical simulations, we have shown that this approach is capable of shifting the threshold voltage to positive values. In addition to that, this technique is more effective when it comes to the concentration required to achieve normally-off operation. Moreover, with this technique, the channel electrons will be better confined below the gate and scattering with fluorine ions will vanish, since fluorine is implanted below the channel layer. Finally, the implantation of fluorine ions below the channel does not affect the vertical breakdown voltage and the off-state current.

7. ACKNOWLEDGMENT

This work was funded by the Laboratory for Analysis and Architecture of Systems (LAAS – CNRS/France) and by GET/EDST/UL- AZM & SAADA association.

8. REFERENCES

[1] H. Chen, J. Wang, C. Xu, M. Yu, Y. Fu, Z. Dong, F. Xu, Y. Hao, and C. P. Wen, "Enhanced device performance of AlGaN/GaN HEMTs using thermal oxidation of electron-beam deposited aluminum for gate oxide," in *9th International Conference on Solid-State and Integrated-Circuit Technology, 2008. ICSICT 2008*, 2008, pp. 1443–1446.

[2] U. K. Mishra, P. Parikh, and Y.-F. Wu, "AlGaN/GaN HEMTs-an overview of device operation and applications," *Proc. IEEE*, vol. 90, no. 6, pp. 1022–1031, 2002.

[3] H. Kambayashi, Y. Satoh, T. Kokawa, N. Ikeda, T. Nomura, and S. Kato, "High field-effect mobility normally-off AlGaN/GaN hybrid MOS-HFET on Si substrate by selective area growth technique," *Solid-State Electron.*, vol. 56, no. 1, pp. 163–167, Feb. 2011.

[4] S. D. Burnham, K. Boutros, P. Hashimoto, C. Butler, D. W. S. Wong, M. Hu, and M. Micovic, "Gate-recessed normally-off GaN-on- Si HEMT using a new O_2-BCl_3 digital etching technique," *Phys. Status Solidi C*, vol. 7, no. 7–8, pp. 2010–2012, 2010.

[5] H. Chen, M. Wang, and K. J. Chen, "Self-aligned enhancement-mode AlGaN/GaN HEMTs using 25 keV fluorine ion implantation," in *Device Research Conference (DRC), 2010*, 2010, pp. 137–138.

[6] X. Hu, G. Simin, J. Yang, M. A. Khan, R. Gaska, and M. S. Shur, "Enhancement mode AlGaN/GaN HFET with selectively grown pn junction gate," *Electron. Lett.*, vol. 36, no. 8, pp. 753–754, 2000.

[7] Y. Ohmaki, M. Tanimoto, S. Akamatsu, and T. Mukai, "Enhancement-Mode AlGaN/AlN/GaN High Electron Mobility Transistor with Low On-State Resistance and High Breakdown Voltage," *Jpn. J. Appl. Phys.*, vol. 45, no. No. 44, pp. L1168–L1170, Nov. 2006.

[8] M. Higashiwaki, T. Mimura, and T. Matsui, "Enhancement-Mode AlN/GaN HFETs Using Cat-CVD SiN," *IEEE Trans. Electron Devices*, vol. 54, no. 6, pp. 1566–1570, 2007.

[9] T. Mizutani, M. Ito, S. Kishimoto, and F. Nakamura, "AlGaN/GaN HEMTs With Thin InGaN Cap Layer for Normally Off Operation," *IEEE Electron Device Lett.*, vol. 28, no. 7, pp. 549–551, 2007.

[10] K. J. Chen, L. Yuan, M. J. Wang, H. Chen, S. Huang, Q. Zhou, C. Zhou, B. K. Li, and J. N. Wang, "Physics of fluorine plasma ion implantation for GaN normally-off HEMT technology," in *Electron Devices Meeting (IEDM), 2011 IEEE International*, 2011, pp. 19.4.1–19.4.4.

[11] SILVACO, "ATLAS User's Manual DEVICE SIMULATION SOFTWARE," Santa Clara, CA,, 2011, pp. 330–331.