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## Fluorine-Based Plasma treatment for AlGa<sub>0.27</sub>Ga<sub>0.73</sub>N E-Mode HEMTs and Low On-Voltage Diodes

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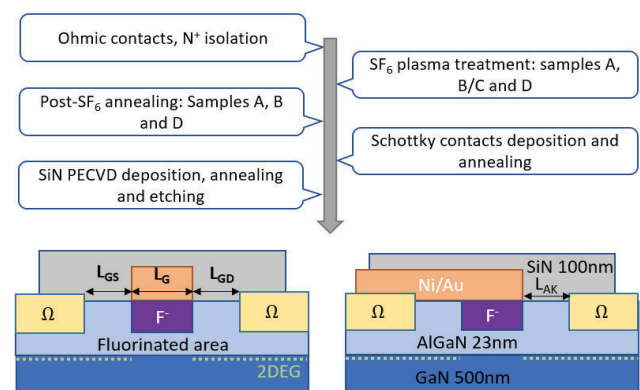
### Abstract

*The onset and pinch-off voltages shift of lateral GaN field-effect rectifier diodes (L-FER) and normally-off HEMTs are studied. It is shown that a short duration of low power SF<sub>6</sub> plasma followed by a low temperature annealing permits to get an effective and stabilized fluorine ion implantation in the AlGa<sub>0.27</sub>Ga<sub>0.73</sub>N barrier, contributing to reduce the back shift of both devices threshold voltages.*

### Introduction

In this work, it is presented enhanced-mode AlGa<sub>0.27</sub>Ga<sub>0.73</sub>N HEMTs (E-HEMT) with fluorine ions implantation using a low power SF<sub>6</sub> plasma, and lateral field-effect rectifier (L-FER) diodes featuring low onset voltage  $V_{on}$  as well. Because of the expansion of GaN-based power devices for switching application, blocked E-HEMT at the zero gate bias could prevent short circuit in case of malfunction, while low  $V_{on}$  rectifier allows high power efficiency. Effect of fluorine-based plasma treatment is well known to introduce anions beneath the gate area into the AlGa<sub>0.27</sub>Ga<sub>0.73</sub>N layer, acting as ionized acceptor [1] pushing-off the carriers from the heterojunction. Then, the electric field applied on the gate by a positive bias is able to restore back the electron channel. In practice, the plasma induced damages involve a decrease of both electron mobility and density and consequently the conduction properties at the heterojunction. The proposed SF<sub>6</sub> treatment consists here to expose samples to a long duration but low radio-frequency plasma power to mitigate the damages within the AlGa<sub>0.27</sub>Ga<sub>0.73</sub>N barrier. This approach improves the on-resistance  $R_{on}$ , optimizes the breakdown voltage BV and still enables the E-mode operation with a positive pinch-off voltage  $V_p$ . Superficial implanted fluorine ions suffer from out-diffusion in case of high temperature process such as the thermal gate annealing. The consequence is a back-shift of the onset voltages on E-HEMTs and L-FERs, so, a low temperature thermal annealing is also investigated. This specific post-SF<sub>6</sub> treatment tends to stabilize  $V_p$  and  $V_{on}$  [2], and considerably reduces the diodes reverse current leakages as well.

### Experimental



**Figure 1.** E-HEMT and L-FER structures on left and right side

The epitaxial stack consists of 23nm Al<sub>0.27</sub>Ga<sub>0.73</sub>N barrier, 500nm GaN buffer and 200nm AlN nucleation layer grown on a Si(111) substrate by Metal-Organic Chemical Vapor Deposition (MOCVD). Device fabrication started with Ti/Al/Ni/Au ohmic contacts deposition and annealed in N<sub>2</sub> atmosphere for 30 seconds at 850°C. Isolation was then performed through N<sup>+</sup> ion implantation. Transmission Line Measurements (TLM) revealed a contact resistance of 0.37 Ω.mm<sup>2</sup>. Four samples were exposed inside an Oxford Plasmalab to a local SF<sub>6</sub> Inductively Coupled Plasma (ICP) under the gate area: sample A was exposed 5 minutes at a RF power of 20W, samples B and C during 5 minutes at 80W and sample D during 8 minutes at 45W. The DC power injected was 80W for each sample. Then, samples A and B were annealed during 90 min at 250°C and 90 min at 500°C respectively. Sample D has experienced both 250°C and 350°C annealing during 250 min. Both thermal treatments used N<sub>2</sub> atmosphere. Sample C acts as a reference and was not annealed. Ni/Au gate were then performed and annealed in N<sub>2</sub> at 400°C during 20 minutes; finally, 100nm SiN passivation layer was deposited through plasma enhanced PECVD and annealed with the same process than the Schottky contacts. HEMTs and diodes schematic structures are shown in Fig.1. The gate length  $L_G$  is 2μm and L-FER fluorinated area is

3  $\mu\text{m}$  length,  $L_{\text{GS}}$ ,  $L_{\text{GD}}$ , and  $L_{\text{AK}}$  are a 1.75  $\mu\text{m}$  spacing. The only structural difference between both devices is the gate to source short contact for the field-effect Schottky/ohmic anode in the case of the L-FER.

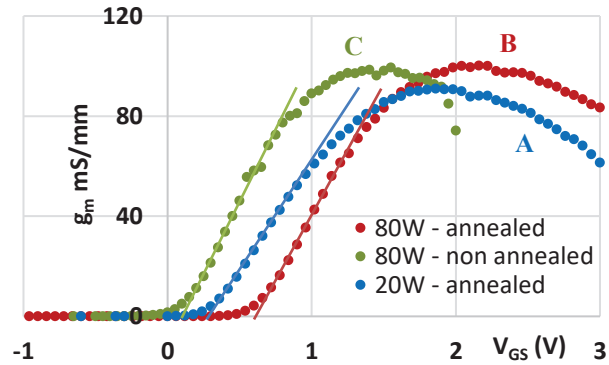
## Results and discussion

DC I-V measurement performed to extract the transfer and the blocking forward characteristics plot are shown in *Fig. 2a* and *Fig. 2b* respectively. The pinch-off voltage  $V_p$  and the maximum transconductance  $g_m$  of the E-mode HEMT are given by the drain to source current  $I_D$  derivative versus the gate to source voltage  $V_{\text{GS}}$ . Considering that every HEMT operates in enhanced-mode, the breakdown voltage and the drain current leakage at blocking state are measured by increasing  $V_{\text{DS}}$  at  $V_{\text{GS}}=0\text{V}$ . No measurement with a negative  $V_{\text{GS}}$  has been recorded. The Schottky barrier height  $\phi_B$  was also calculated based on the Shockley equation on implanted and non-treated Schottky contact area. On sample D,  $\text{SF}_6$ -treated area Schottky barrier height is about 1.07eV, and 1.02eV for standard Schottky on AlGaIn anode.

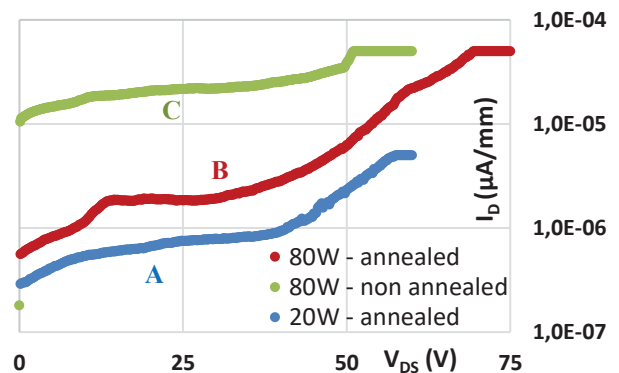
A 2  $\mu\text{m}$  gate length transistor on sample A exhibits a lower threshold voltage  $V_p$  of 0.24V compared to sample B with 0.59V. This is consistent with literature<sup>[3,4]</sup>, where the higher plasma power is reported to produce the larger voltage shift. Sample B shows a very homogeneous 0.6V pinch-off versus 0.14V for sample C indicating firstly that the post  $\text{SF}_6$  treatment annealing gives better stability of that parameter and then it is possible to reach the E-mode behaviour with a less energetic plasma limiting the material damages. Furthermore, the annealing did not affect the maximum transconductance  $g_m$ , which is about 100mS/mm and 98mS/mm for samples B and C respectively. The transconductance  $g_m$  is a bit lower on sample A with 91mS/mm. As a reference, electrical parameters were extracted from normally-on HEMTs which has not been exposed to the  $\text{SF}_6$  treatment. On sample A,  $V_p$  and  $g_m$  have values of -2.7V and 68 mS/mm respectively, meaning an absolute voltage shift of 2.9V and an improvement on the normally off E-HEMTs transconductance.

Results on the breakdown voltage BV are shown in *Fig. 2b*. Curves from samples A and C have the same variation behaviour: a linear and an exponential part before and after BV respectively, indicating the resistive leakage due to the non-depleted carriers under the gate area. BV on sample A is about 45.5V for a leakage current of 0.14  $\mu\text{A}/\text{mm}$ , and 59 mV of pinch-off back-shift has been measured after breakdown. E-HEMT from sample B breakdown at 58.5V with a leakage current of 1.9  $\mu\text{A}/\text{mm}$ , the back-shift of  $V_p$  is 69 mV. Finally, on sample C, the BV value is 49.7V at 6.95  $\mu\text{A}/\text{mm}$  of drain current, and no decrease was observed on  $V_p$ . Therefore, the

plasma power improves the breakdown voltage, but it was not expected that the drain current leakage could be higher, as this parameter involves the carrier depletion from the channel. Furthermore, all the samples are stable face to high voltages.  $V_p$  is stable, below 3% of fluctuation on the initial absolute shift, and there is no significant difference on the maximum of  $g_m$ .



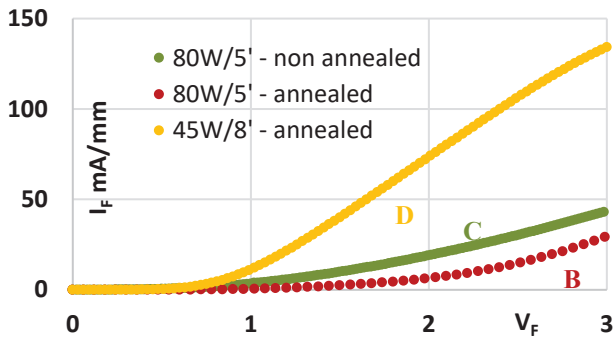
**Figure 2a.** E-HEMT  $g_m$  vs  $V_{\text{GS}}$  characteristic at  $V_{\text{DS}} = 5\text{V}$  from samples A, B and C



**Figure 2b.** Forward  $I_D$ - $V_{\text{DS}}$  characteristics at the blocking state  $V_{\text{GS}} = 0\text{V}$  (logarithmic scale) from samples A, B and C

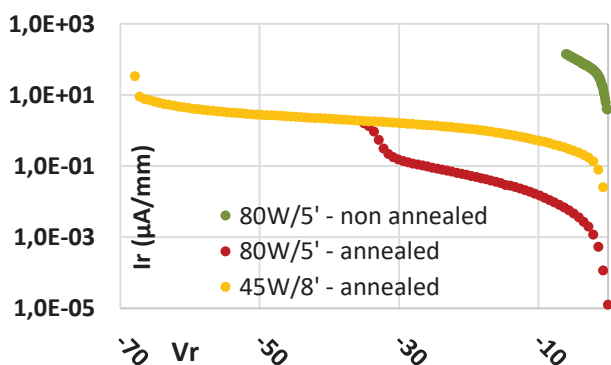
To keep the same analysis method and because the L-FER structure is practically similar to the E-mode HEMT, the forward current derivative is used to extract the threshold voltage  $V_{\text{on}}$  of the diodes, as for transconductance on HEMTs. *Fig. 3a* presents the L-FER forward characteristics of the three samples. Sample B exhibits  $V_{\text{on}}$  about 0.7V and sample C 0.33V indicating here again the efficiency of the annealing on stabilizing the threshold voltage<sup>[3]</sup>, despite the lowest value that is targeted. Sample D shows an intermediate  $V_{\text{on}}$  of 0.49V, so the longer duration but less energetic plasma treatment gives close results from samples B and C treatment. This last method improves substantially the on-resistance  $R_{\text{on}}$  that is about 14  $\Omega\cdot\text{mm}$  against 29  $\Omega\cdot\text{mm}$  for sample B. Sample C has a  $R_{\text{on}}$  of the same order as B with 35  $\Omega\cdot\text{mm}$ . The annealing seems not to affect significantly this parameter. This is consistent with

the observation made on the E-HEMTs transconductance extracted with the same method.



**Figure 3a.** Forward L-FER current from samples B, C and D

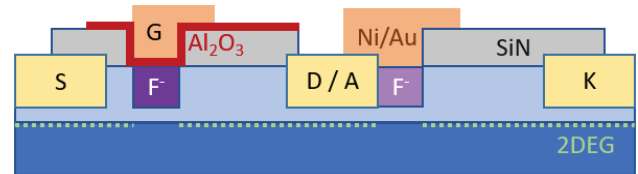
Furthermore, reverse characteristics plot on the Fig. 3b show that the lower SF<sub>6</sub> plasma power versus duration ratio improves the breakdown voltage. Sample D exhibits BV of 66V against 32V for sample B. The reverse current measured at breakdown is about 7.6 μA/mm on sample D, which is approximately 35 times higher than diodes on sample B with 0.21 μA/mm meaning that the most powerful plasma permits a smaller reverse current leakage and counteracts with the effectiveness of the sample D treatment. Breakdown voltages could not be measured on sample C because of very high reverse leakage current - above 100 μA/mm at only 5V of reverse voltage risking to damage the tool. At equal voltage, the reverse current is decreased by about four orders of magnitude for sample B which was annealed compared to sample C. All of the measured reverse currents show linear variations proving that resistive leakage occurs due to an incomplete channel depletion.



**Figure 3b.** Reverse L-FER current from samples B and D

Dynamic I-V measurements will be performed soon to analyse trapping effect and to compare these different processes. Next step will consist to analyze surface compounds through techniques such as XPS and SIMS. The aim is to display the annealing influence on fluorine ion distribution in AlGaN and its covalent links in order to explain the behaviour

improvements for both HEMTs and L-FER. Finally, according to the previous results, the process will be optimized to reach higher BV, near-zero V<sub>on</sub> and low on-resistance GaN diode and more than 1V V<sub>p</sub> for E-mode HEMTs. New structures (Fig. 4) with a large development are actually studied to reach high current and breakdown voltage, and to co-integrate both devices in a full DC converter switching cell.



**Figure 4.** Switching converter cell E-HEMT / L-FER

## Conclusions

This work demonstrates an effective approach of fluorine-based plasma treatment to get co-integrated enhanced-mode HEMTs and low onset voltage diodes. It also improves the transconductance on E-HEMTs compared to normally-on devices. As the duration of the exposition is the more influent parameter, the low RF power enables high breakdown voltage and it reduces the on-resistance. This study also demonstrates that the specific thermal annealing has a significant impact on the onset voltage fluctuation, decreasing reverse current leakage and does not affect the on-resistance.

## Acknowledgements

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