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# P-Doped Region below the AlGa<sub>N</sub>/Ga<sub>N</sub> Interface for Normally-Off HEMT

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## Keywords

«High electron mobility transistor (HEMT) », «Gallium Nitride (Ga<sub>N</sub>)», «Wide bandgap devices », «Device simulation»

## Abstract

Development of a new design for enhancement-mode AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT is presented. The normally-off operation was achieved by burying a p-Ga<sub>N</sub> region below the AlGa<sub>N</sub>/Ga<sub>N</sub> interface only below the gate. Simulation results show that the proposed technique is capable of shifting the threshold voltage to positive values, making the HEMT normally-off. To address the advantages and drawbacks of the proposed structure a comparison with the normally-off Gate injection transistor (GIT) was performed. The proposed structure seems to be more effective when it comes to the p-doping concentration required to achieve normally-off operation and offers superior confinement for the two dimensional electron gas. On the other hand, the low forward gate voltage limits the increase of the threshold voltage.

## Introduction

AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs are very promising candidates for high frequency applications with high power and low noise, such as microwave and millimeter wave communications, imaging and radars [1]. With the high field strength offered by Ga<sub>N</sub> and the high mobility of the two-dimensional-electron-gas (2DEG) presented in the HEMT, this device can attain high breakdown voltage with low on state resistance and high switching frequency, surpassing the limitation of conventional silicon devices.

While power switching applications strongly demand normally-off operation [2], conventional HEMTs attain a channel populated with electrons at zero gate voltage making them normally-on. Several normally-off structures have been proposed such as recessed gate structures [3], fluorine ion treatment [4], pn junction gate structures [5], thin AlGa<sub>N</sub> barrier [6], AlN/Ga<sub>N</sub> structure [7] and Gate injection transistor [8].

The effectiveness of the agent used to obtain normally-off, whether it's recessing the gate, introducing a cap layer or implanting fluorine, increases as the agent come closer to the AlGa<sub>N</sub>/Ga<sub>N</sub> interface. Unfortunately, in introducing a cap layer or recessing the gate, coming closer to the interface means decreasing the barrier thickness which strongly affect the density of the 2DEG.

In the case of fluorine implantation, getting closer to the interface increases the probability of fluorine ions getting into the channel and hence the degradation of the mobility of the 2DEG [9]. In this work, normally-off operation is achieved by introducing a p-doped region in the unintentionally doped (UID) GaN layer, below the AlGaN/GaN interface, only under the gate electrode. Using this approach, the agent (p-doped region) can approach the AlGaN/GaN interface without affecting the thickness of the barrier.

## Simulation Strategy

To do this study, ATLAS, a physically-based TCAD simulation tool from Silvaco, was used. Physical models used in the simulation include Shockley-Read Hall recombination, Fermi-Dirac statistics and field-dependent mobility [10]. The simulator was calibrated using a normally-on HEMT device shown in figure 1.

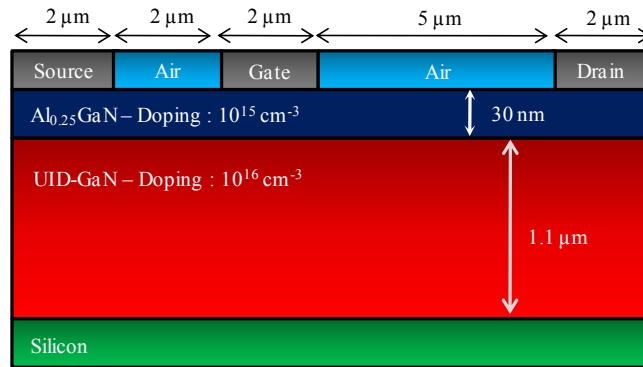


Fig. 1: Schematic cross section of the normally-on HEMT used to calibrate the simulator.

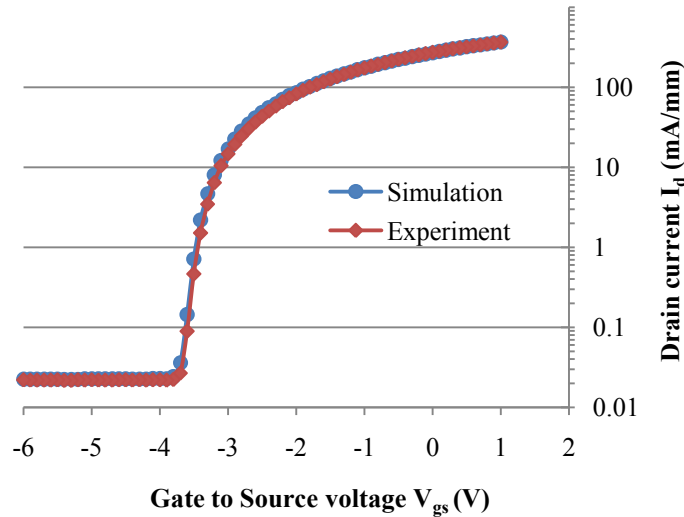


Fig. 2: Comparison of the experimental and simulated  $I_d(V_{gs})$  transfer characteristics of the conventional normally-on HEMT: fitting the simulated threshold voltage, transconductance and off

To match the simulated threshold voltage ( $V_{th}$ ), transconductance and the off-state current with the ones experimentally measured (see figure 2), the energy and the concentration of the acceptor traps, as well as the density of the two dimensional electron gas, were tuned. Some of the parameters used during the simulation are shown in Table 1.

**Table I: Parameters used during simulation**

Parameter	Value
Band offset	$0.7 (E_g(\text{Al}_x\text{GaN}) - E_g(\text{GaN}))$ [eV]
x-mole fraction of Aluminum in AlGaN "x"	0.25 - 0.18
Band Gap of $\text{Al}_x\text{GaN}$	$6.2x + 3.4(1-x) - 1.3x(1-x)$ [eV]
Dielectric Constant of $\text{Al}_x\text{GaN}$	$9.5 - 0.5x$
Interfacial charge density	$\mathbf{K} (P_{\text{GaN}} - P_{\text{AlGaN}}) / q$ [ $\text{cm}^{-2}$ ]
Fitting parameter $\mathbf{K}$	0.61

The schematic cross-section of the proposed normally-off HEMT design is shown in figure 3. The localized p-GaN region has been previously created by other groups using Mg ion implantation to create the current blocking layer (CBL) in AlGaN/GaN current aperture vertical electron transistors (CAVET) [11].

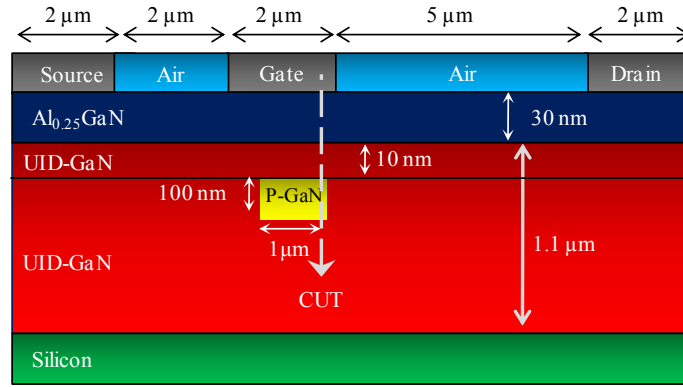


Fig. 3: Schematic cross-section of the HEMT with a buried p-GaN region with some physical and geometrical parameters.

The thickness and width of the P-GaN region are 100 nm and 1 μm respectively. The distance between the AlGaN/GaN interface and the top of the p-GaN region is equal to 10 nm. The doping concentration of the p-GaN region will be increased until normally-off operation is achieved. To point out the advantages and drawbacks of the proposed structure, it will then be compared to the normally-off Gate Injection Transistor (GIT).

## Results and discussion

### HEMT with a buried p-GaN region:

Figure 4 shows the shift in the threshold voltage due to the introduction of the p-GaN region. It is clear that the threshold voltage increase with increasing the p-doping concentration to reach 0.5 V at a doping concentration of  $2.5 \times 10^{18} \text{ cm}^{-3}$ . To explain this shift, the band diagram, along CUT in figure 3, is shown in figure 5. It is well known that, in p-type semiconductors, the Fermi level shifts towards the valence band. However, since at equilibrium the Fermi level is constant, this shift will manifest itself through uplifting the conduction band. The uplift of the conduction band in the p-doped region will elevate the triangular well at the AlGaN/GaN interface. The elevation of the triangular well with respect to the Fermi level causes the shift in the threshold voltage. However, if the uplift in the p-doped region is insufficient to elevate the triangular well above the Fermi level the HEMT remains normally-on (p-doping  $< 2 \times 10^{18} \text{ cm}^{-3}$ ).

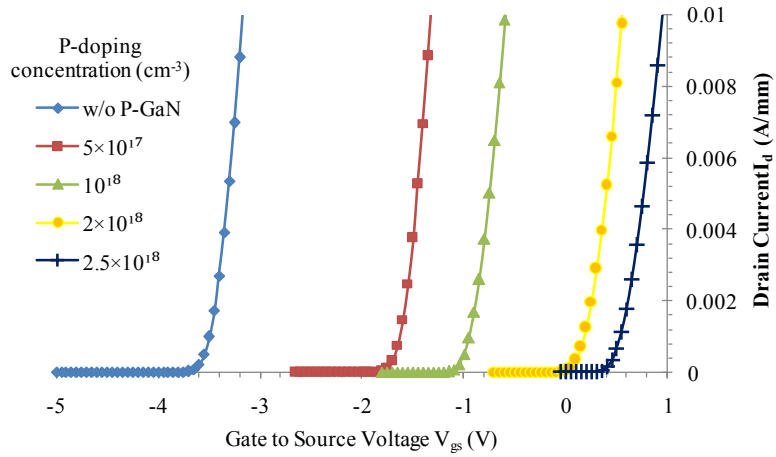


Fig. 4: The increase of the threshold voltage with the doping concentration due to the buried p-GaN region. Normally-off operation with  $V_{th}=0.5$  is achieved at a p-doping concentration of  $2.5 \times 10^{18} \text{ cm}^{-3}$

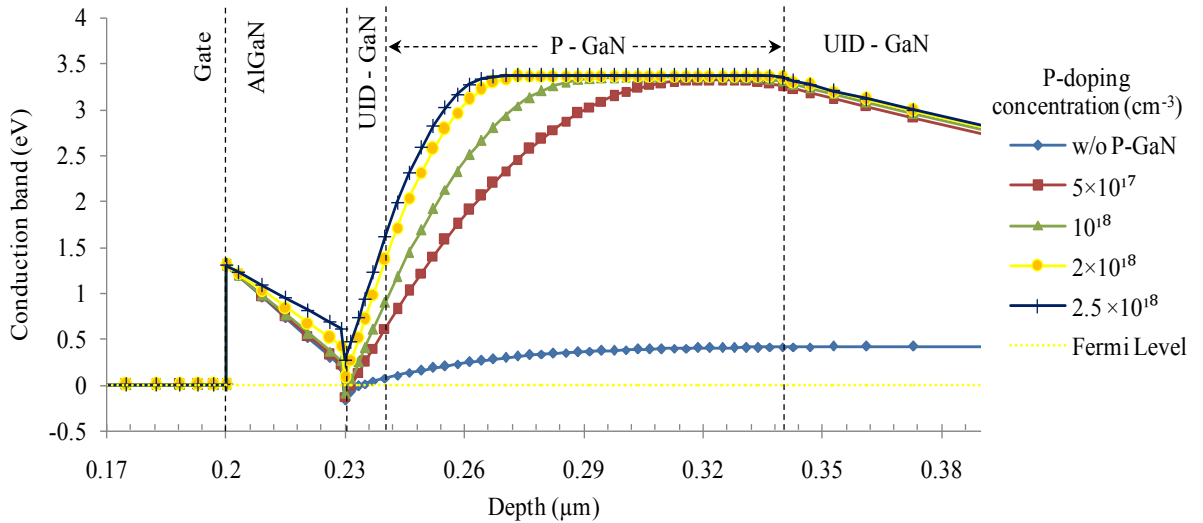


Fig. 5: Conduction band along CUT - see figure 3 - at various p-doping concentrations showing the uplifting of the triangular well above the Fermi level for doping concentrations higher than  $2 \times 10^{18} \text{ cm}^{-3}$

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 doping concentration of  $5 \times 10^{17} \text{ cm}^{-3}$  is needed to achieve normally-off operation with a threshold voltage of 0.5 V. (more details are shown in the coming section)

Figure 5 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:  $V_{gs} = V_{th} - 1 \text{ V}$ .

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.

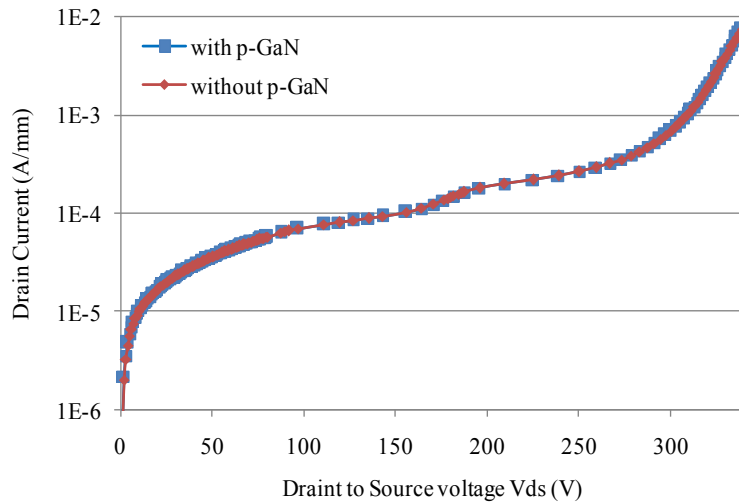


Fig. 5: Simulated  $I_d(V_{ds})$  characteristics in the off-state, showing the off-state current and the breakdown voltage of the normally-on HEMT and the normally-off HEMT with a buried p-GaN region.

### Comparison between the Gate Injection Transistor and the proposed structure:

A well known normally-off HEMT is the Gate Injection Transistor (GIT). This transistor also utilized a p-region to achieve normally-off operation. However, in the GIT the p-region is introduced above the barrier layer rather than below the channel which is the case in our proposed structure.

In this section a comparison with the GIT is performed aiming to point out the advantages and drawbacks of our proposed structure. In the GIT proposed in [8] the optimized thickness and x-mole fraction of the AlGaIn layer are 25 nm and 0.15 respectively. The x-mole fraction of the p-AlGaIn cap layer is 0.15.

For a fair comparison between our proposed structure and the GIT, the same physical parameters are used for both structures (thickness and doping of GaN and AlGaIn). In both cases, the thickness and width p-GaN region are 100 nm and 1  $\mu\text{m}$  respectively. The p-doping concentration will be increased until normally-off operation in both structures is achieved. The chosen “normally-off” criterion is a threshold voltage of 0.5 V.

The schematic cross-section of the simulated normally-off GIT is shown in figure 6. As for our proposed structure the schematic cross-section is the same as the one shown in figure 3 expect for the thickness and x-mole fraction that are reduced to 25 nm and 0.15 respectively.

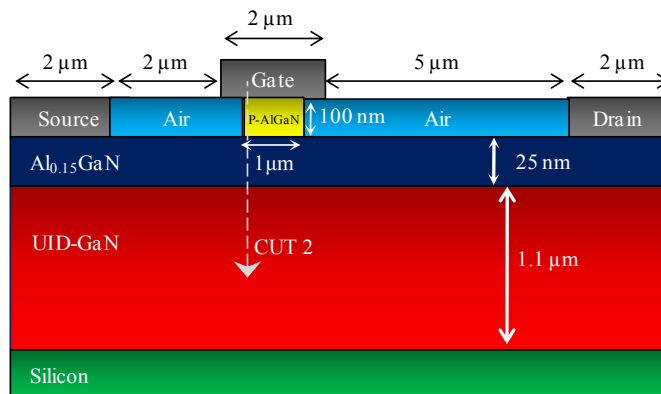


Fig 6: Schematic cross-section of the simulated gate injection transistor (GIT). This structure is compared to our proposed structure.

Figures 7 and 8 show the variation of the threshold voltage and the forward gate voltage of the GIT and our proposed structure respectively. These values are extracted at  $V_{ds}=1$  V. To achieve a threshold voltage of 0.5 V, a doping concentration of  $2 \times 10^{18}$   $\text{cm}^{-3}$  is required in the case of GIT while in our proposed structure, only  $5 \times 10^{17}$   $\text{cm}^{-3}$  is sufficient. Therefore, our proposed structure is more efficient when it comes to doping concentration required to achieve normally-off operation. On the other hand, the forward gate voltage is much higher in the case of the Gate Injection Transistor. This is attributed to the use of p-AlGaN gate in the GIT rather than a Schottky gate. The low forward gate voltage in our proposed structure limits the increase in the threshold voltage to higher values.

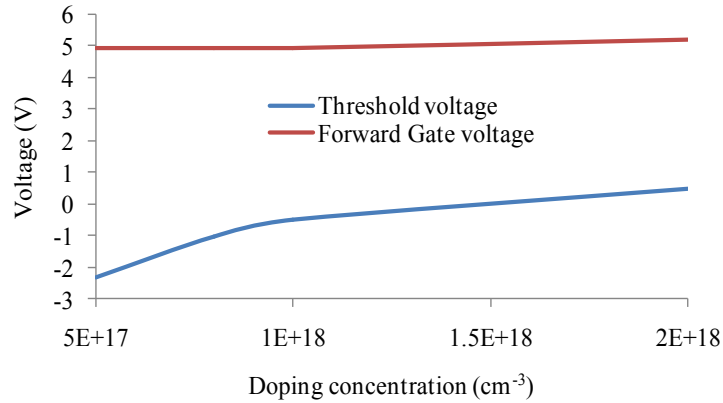


Fig. 7: Threshold voltage and forward gate voltage of the GIT at various doping concentrations. A threshold voltage of 0.5 V was achieved at doping concentration of  $2 \times 10^{18}$   $\text{cm}^{-3}$  at this doping concentration the forward gate voltage was 5.1 V. Values are extracted at  $V_{ds} = 1$  V

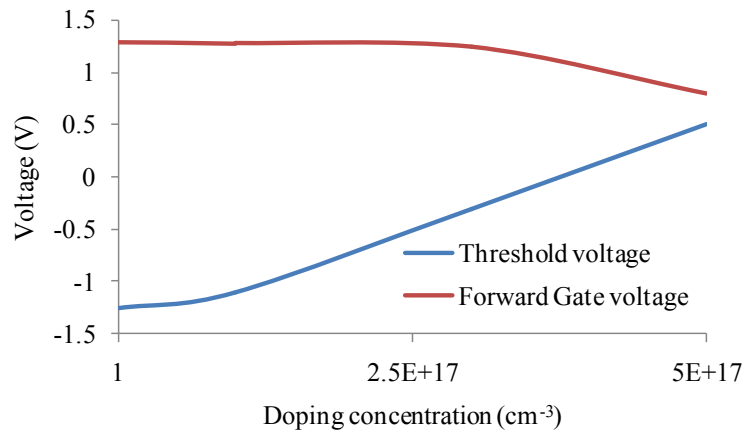


Fig. 8: Threshold voltage and forward gate voltage of the GIT at various doping concentrations. A threshold voltage of 0.5 V was achieved at doping concentration of  $5 \times 10^{17}$   $\text{cm}^{-3}$  at this doping concentration the forward gate voltage was 0.8 V. Values are extracted at  $V_{ds} = 1$  V

To address the quality of the triangular well in which the channel electrons are confined. The band diagram for both structures, along CUT in figure 3 and CUT2 in figure 6, is shown in figure 9. It is clear that the confinement of the 2DEG is superior in our case. This better confinement will lead to higher mobility. However, in our simulation the mobility of the 2DEG, in all cases, was fixed to 1500  $\text{cm}^2/\text{v}\cdot\text{sec}$ . This hinders the comparison of the on-state resistance and transconductance for the two structures.

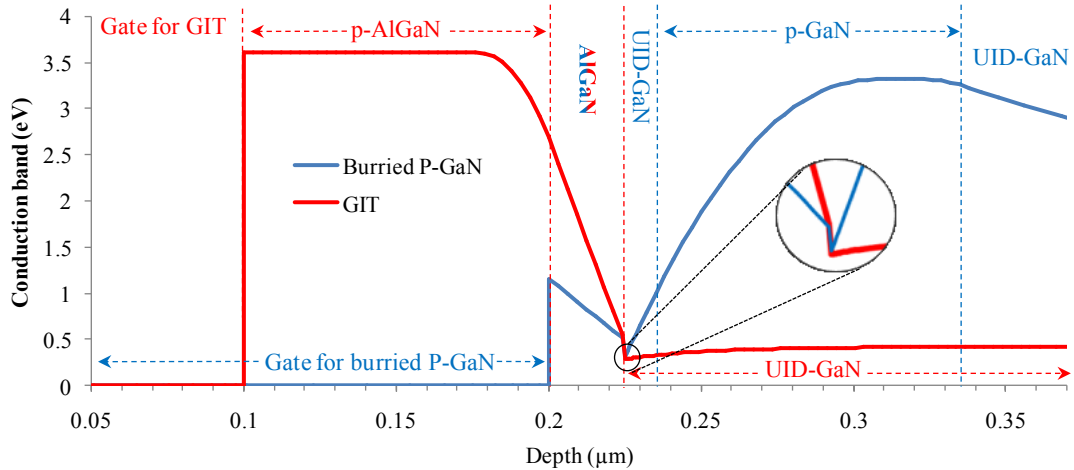


Fig. 9: Band diagram of the gate injection transistor and the HEMT with a buried p-GaN region corresponding to a threshold voltage of 0.5 V with a p-doping concentration of  $2 \times 10^{18} \text{ cm}^{-3}$  and of  $5 \times 10^{17} \text{ cm}^{-3}$  respectively. The zoomed part shows a better triangular well in the case of HEMT with buried p-GaN region

## Conclusion

In this work, a new normally-off HEMT design was proposed. In order to achieve normally-off operation, a p-GaN region was introduced below the gate electrode and 10 nm under the AlGaIn/GaN interface. After calibrating the simulator using experimental data from a normally-on HEMT, the p-GaN region was introduced. Simulation results have shown that this technique is capable of shifting the threshold voltage to positive values making the HEMT normally-off. When compared to the gate injection transistor, this design is more effective when it comes to the doping concentration required to achieve normally-off operation and offers better confinement to the two dimensional electron gas. On the other hand, the proposed structure attains a low forward gate voltage when compared to the GIT. This low forward gate voltage, which limits the increase in the threshold voltage, can be eliminated by introducing an insulating material under the gate such as  $\text{Al}_2\text{O}_3$ , SiN or  $\text{HfO}_2$ .

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