

# Simulation of Electrical Characteristics on Inhomogeneous Strains in Normally-off HEMTs with p-GaN Gate

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**Abstract.** Strain is one of the important factors affecting the two-dimensional electron gas (2DEG) transform in AlGaIn/GaN material based high electron mobility transistors (HEMTs) by polarization effects. In this paper, the effects of inhomogeneous biaxial strain in different regions of the AlGaIn barrier layer on electrical properties of normally-off HEMTs with p-GaN gate were discussed. The results show that biaxial strain applied in three regions has different influence on transfer, output and breakdown characteristics of the device. The strain applied in region under gate has the most significant impact on threshold voltage and drain saturation current with a decreasing of 39% and an increasing of 97% respectively as the strained lattice constant increases from 3.173061Å to 3.187229Å. While, strain applied between gate and drain electrode can improve the off-state breakdown voltage by 12% with the increasing of strained lattice constant.

## 1 Introduction

High Electron Mobility Transistors (HEMTs) based on AlGaIn/GaN heterostructures became attractive candidates for high switching frequency, high breakdown voltage and high power due to their excellent electrical properties, compared to their silicon (Si) counterparts [1-3]. In the interface of heterojunction, a two dimensional electron gas (2DEG) with a high sheet carrier density ( $\sim 10^{13} \text{cm}^{-2}$ ) and mobility (above  $1000 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ ) is generated, owing to the spontaneous and piezoelectric polarization, and donor-like AlGaIn surface states acting as source of electrons. Generally, most AlGaIn/GaN HEMTs exhibit normally-on operation since 2DEG is intrinsically existed in the AlGaIn/GaN interface when the HEMT is operating at a gate bias of less than zero volts [4-5]. However, for power electronics applications normally-off devices is needed considering of safety conditions and simplicity in the gate driver circuits.

Several approaches have been reported to obtain normally-off GaN-based HEMTs, covering the Recessed gate, Fluorine ions injection, and Recessed Hybrid MIS (metal-insulator-semiconductor) HEMT configurations. However threshold voltage ( $V_{th}$ ) stability can be a safety concern in all this kind of devices [6-7]. To date the most typical way to yield a normally-off device is the use of a p-GaN gate, grown on the AlGaIn/GaN heterostructure only in the gate contact region, which can deplete the conduction channel when unbiased.

Previous studies demonstrate that 2DEG can be affected by strain [8]. Tong et al. [9] applied a strain model to study the electron transport in normally-on

HEMT device when barrier is uniformly biaxial strained. Simin G. et al [10] revealed that gate bias-induced inhomogeneous strain in the AlGaIn barrier will cause a decrease in polarization charge and reduction in 2DEG in normally-on HEMT device by experiments. Ahmeda K. et al [11] found that applying strain in drain region will cause changes in the total polarization, thus affecting 2DEG density in the channel. However, as far as we known, there are few reports on the strain effect in the AlGaIn barrier of normally-off HEMT with a p-GaN gate. And the effect of non-uniform strain on device characteristics is often omitted because the strain is treated as uniform directly.

In this work, numerical simulations of the effects of inhomogeneous biaxial strain in AlGaIn barrier layer on the electrical properties in a normally-off HEMTs with p-GaN gate are discussed. The biaxial strain in three regions, region under the gate (Region-G), region between the gate and the drain electrode (Region-GD) and region between the gate and the source electrode (Region-GS) are found to change with the strain in the lattice constant. And the impact of strain on electrical parameters, such as threshold voltage ( $V_{th}$ ), drain saturation current ( $I_{sat}$ ) and off-state breakdown voltage ( $V_{br}$ ) is simulated and comparatively investigated using Sivalco-TCAD-altas.

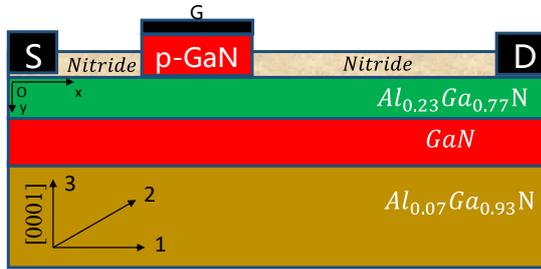
## 2 Structure Model and Analysis Method

The schematic diagram of normally-off HEMT with p-GaN gate is presented in Fig.1. The S, G, and D denotes the source electrode, the gate electrode and the drain electrode respectively. The Nitride ( $\text{Si}_3\text{N}_4$ ) is the

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passivation layer, with which the surface state of AlGa<sub>N</sub> barrier can be improved to suppress the current collapse phenomenon. The Al<sub>0.07</sub>Ga<sub>0.93</sub>N buffer layer allows a better confinement of 2DEG in the channel [12,13]. The structure parameters used in the simulation are listed in Table 1.

The relationship between strain and 2DEG is defined by a strain model [9]. When the strained lattice constant (a) in AlGa<sub>N</sub> barrier layer changes, the external biaxial strain will change correspondingly. The total polarization charge, including charge of piezoelectric polarization and spontaneous polarization, changes as well, and ultimately affecting the concentration of 2DEG. Coupling with Poisson's equation and current continuity equation, the "I-V" characteristics of the normally-off HEMT with p-GaN gate can be obtained.

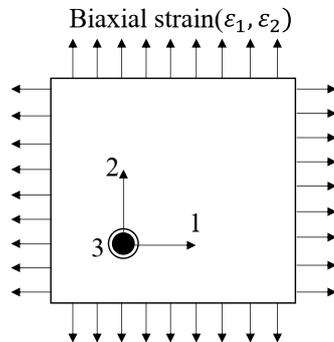


**Fig. 1.** Schematic diagram of the normally-off AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT with p-GaN gate

Due to the growth of two piezoelectric materials Ga<sub>N</sub> and AlGa<sub>N</sub> layers, a lattice mismatch strain is developed in the heterostructure. as shown in Eq.(1), the strains developed in the AlGa<sub>N</sub> layer due to lattice mismatch are:

$$\varepsilon_1 = \varepsilon_2 = \frac{a_{\text{GaN}} - a_{\text{AlGaN}}}{a_{\text{AlGaN}}}, \quad \varepsilon_3 = -2 \frac{C_{13}}{C_{33}} \varepsilon_1 \quad (1)$$

Where  $a_{\text{GaN}}$  and  $a_{\text{AlGaN}}$  are the lattice constant for Ga<sub>N</sub> and AlGa<sub>N</sub> without external strain, respectively and  $C_{13}$  and  $C_{33}$  are the elastic constants of AlGa<sub>N</sub> layer. Fig.2 illustrates the state of normally-off HEMT under external biaxial strain and the external strain for AlGa<sub>N</sub> can be defined as Eq.(2):



**Fig. 2.** Top-view of the normally-off AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT under biaxial applied strain in the 1- and 2-directions (basal plane)

Where  $a$  and  $a_0$  represent the strained and unstrained lattice constant of AlGa<sub>N</sub> barrier layer respectively, and  $(a - a_0)/a_0$  is restricted to a small range [13] less than

0.06% according to the stain model [9] on which the investigations are based.

**Table 1.** Device structure parameters used in simulation

Device parameters	Value
Length of source, $L_s$	1 $\mu\text{m}$
Length of gate, $L_g$	1.4 $\mu\text{m}$
Length of drain, $L_d$	1 $\mu\text{m}$
Source-Gate spacing, $L_{gs}$	1 $\mu\text{m}$
Gate-Drain spacing, $L_{gd}$	6 $\mu\text{m}$
p-GaN thickness	35 nm
p-GaN uniform doping	$3 \times 10^{17} \text{cm}^{-3}$
Al <sub>0.23</sub> Ga <sub>0.77</sub> N barrier thickness	15 nm
GaN thickness	10 nm
Al <sub>0.07</sub> Ga <sub>0.93</sub> N buffer thickness	2 $\mu\text{m}$
Si <sub>3</sub> N <sub>4</sub> thickness	0.31 $\mu\text{m}$
Gate width	1000 $\mu\text{m}$

Assuming the Ga<sub>N</sub> layer is under total strain relaxation and  $P_{\text{SP}}(\text{GaN})$  is a constant unaffected by strain, the polarization induced charge density can be calculated by Eq. (3) [9].

$$\begin{aligned} \sigma &= P_{\text{SP}}(\text{GaN}) - P_{\text{SP}}(\text{AlGaN}) - P_{\text{PE}}(\text{AlGaN}) \\ &= (-0.034) - (0.056x - 0.034) - (\varepsilon_1 + \varepsilon_1')e_{31} \\ &\quad - (\varepsilon_2 + \varepsilon_2')e_{31} - (\varepsilon_3 + \varepsilon_3')e_{33} \\ &= (-0.034) - (0.056x - 0.034) \\ &\quad - 2 \frac{a - a_0}{a_0} (e_{31} - e_{33} \frac{C_{13}}{C_{33}}) \end{aligned} \quad (2)$$

Where  $P_{\text{SP}}$  and  $P_{\text{PE}}$  denote spontaneous polarization and piezoelectric polarization respectively. The spontaneous polarization on the Ga<sub>N</sub> and AlGa<sub>N</sub> layer ( $P_{\text{SP}}(\text{GaN})$ ) and ( $P_{\text{SP}}(\text{AlGaN})$ ) is an intrinsic parameter[13],  $x$  is the Al alloy composition of  $\text{Al}_x\text{Ga}_{(1-x)}\text{N}$  barrier,  $e_{31}$  and  $e_{33}$  are the piezoelectric coefficients of AlGa<sub>N</sub> layer,  $C_{31}$  and  $C_{33}$  are the elastic constants of AlGa<sub>N</sub> layer[15] Then the density of 2DEG in the channel can be given by[14] Eq. (4).

Where  $\sigma$  is the total polarization induced charge density defined by Eq. (3),  $\epsilon$  is the relative dielectric constant of AlGa<sub>N</sub> layer,  $t_{\text{AlGaN}}$  is the thickness of the barrier layer,  $\phi_b$  is the Schottky barrier of a gate contact,  $E_F$  is the Fermi level regarding to the Ga<sub>N</sub> conduction-band-edge energy in the interface and  $\Delta E_c$  is the band offset between AlGa<sub>N</sub> and Ga<sub>N</sub> interface.

In this paper, the electrical characteristics under external inhomogeneous biaxial strain are studied by adjusting the strained lattice constant ( $a$ ) in different regions of barrier separately. The  $a_0$  is set to 3.17129Å [15], and the sets of strained lattice constant  $a$  are

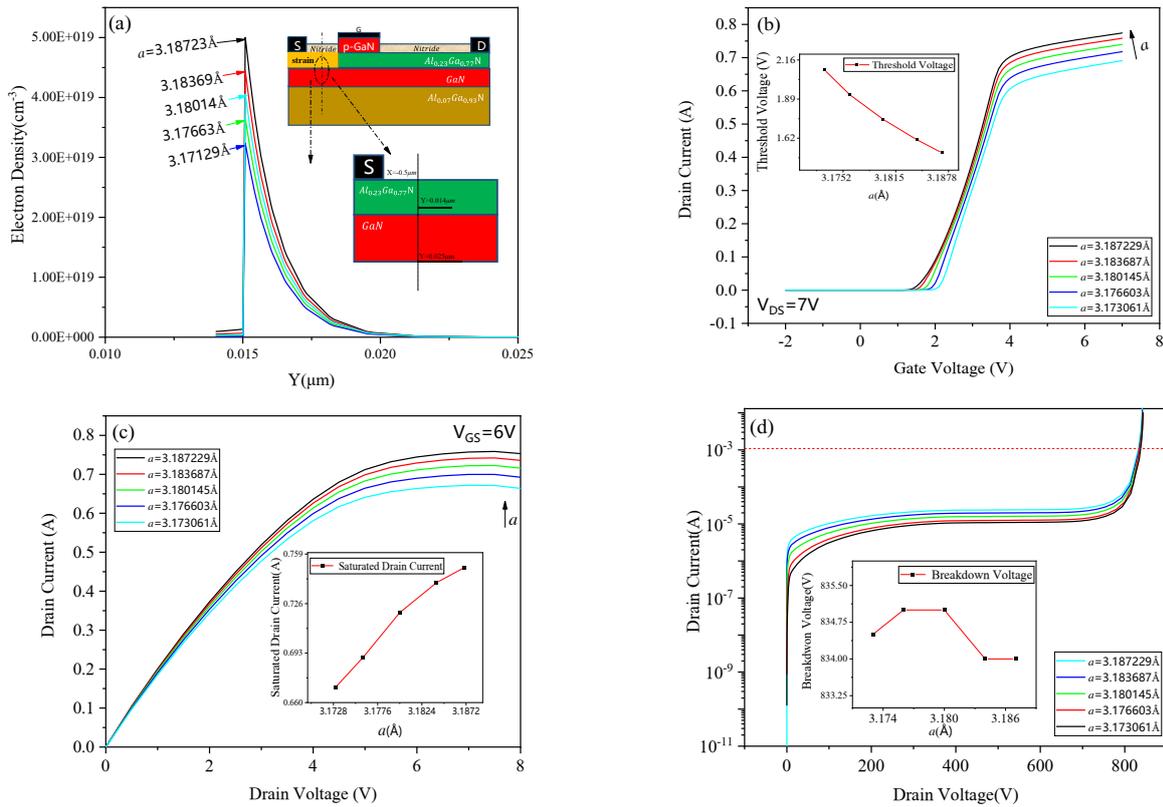
3.173061Å, 3.176603Å, 3.180145Å, 3.183687Å, and 3.187229Å, with a step length of 0.003542Å.

### 3 Discussion

The electrical characteristics of the device were shown in Fig.3 when the  $a$  of AlGa<sub>0.23</sub>N barrier in Region-GS increases while the  $a$  of the other two regions keeps the same as before (3.189Å). Fig.3(a) demonstrates the density of 2DEG increases with  $a$  which is in coherent with Eq.(3). Fig.3(b) shows the transfer characteristics of the normally-off HEMTs, where the gate-source voltage

$V_{gs}$  varies from -2V to 8V and the drain-source voltage  $V_{ds}$  is 7V..

The HEMT, having Al<sub>0.23</sub>Ga<sub>0.77</sub>N/GaN with a p-GaN gate, shows a typical normally-off operation with a threshold voltage above 1V, as defined by the gate bias intercept of a linear extrapolation of drain current at the point of peak  $g_m$  (not shown in Fig.3). Strain-enhanced  $V_{th}$  can be derived from reduced density of 2DEG in the Region-GS, and the gate voltage required to open the channel shift positively, which agrees with the results from choi[16]and Liu[17]. As shown in Fig.3(b),  $V_{th}$  increases from 1.4V to 2.1V with a rate up to 37% when  $a$  decreases from 3.187229Å to 3.173061Å



**Fig. 3.**(Color online) The impact of strained lattice constant  $a$  in Region-GS on electrical characteristics.(a) the cross-sectional 2DEG density at  $x = -0.5\mu\text{m}$  where the peak 2DEG density was located close to the AlGa<sub>0.23</sub>N/GaN interface.(b) transfer characteristics.(c) output characteristics.(d)breakdown characteristics. The insets give the change of  $V_{th}$ ,  $I_{sat}$ ,  $V_{br}$  against strained lattice constant  $a$ .

Furthermore, the drain saturation current  $I_{sat}$ , which is defined as the maximum current in the saturated region at  $V_{gs} = 6V$  and  $V_{ds}$  varies from 0 to 8V, become smaller. This reduction in  $I_{sat}$  may be caused by the lower density of 2DEG due to a smaller  $a$  in the Region-GS which affecting the sheet resistance and current drive, and literature [17,18] reported the similar results.  $I_{sat}$  grows about 12% when  $a$  varies from 3.173061Å to 3.187229Å. In addition, the breakdown voltage  $V_{br}$  of the device, defined as the applied drain voltage when the drain current reaches 1mA at the gate voltage of 0V with source electrode grounded, are investigated. The results in Fig.3(d) denote that local strain in Region-G has a little impact on the off-state breakdown characteristics. The

effect on electrical characteristics by the strain in Region-G has a little impact on the off-state breakdown characteristics.

The effects on electrical characteristics by the strain in Region-G and Region-GD were simulated using the same method. A comparative analysis among the influence of strain working in different regions of AlGa<sub>0.23</sub>N barrier is carried out. Fig.4(a) shows the effect of inhomogeneous strain on threshold voltages  $V_{th}$ . It is clearly observed that the threshold voltage  $V_{th}$  reduces up to 39% when  $a$  in Region-G decreases from 3.187229Å to 3.173061Å, while only 33% and 37% with the same change of  $a$  in Region-GD and Region-GS respectively. The results indicate that strain in Region-G has the most significant

influence on  $V_{th}$ . In addition, the similar results had been obtained by Choi S. who found that the decreasing of total polarization charge and the 2DEG concentration resulted in the positive shifts of  $V_{th}$  by increasing the In composition ( $In_x Al_{(1-x)} N$ ) in experiments [16]. Fig.4(b) shows the influence of strain in different regions on drain saturation current  $I_{sat}$ . Strain in Region-G has the most influence on  $I_{sat}$  with an increasing of 97% when  $a$  grows from 3.173061Å to 3.187229Å. And the data collected from Liu[17] shows that external strain from compressive to tensile increases drain current, which is in

line with our simulation. Fig.4(c) gives the curves of breakdown voltage against  $a$  of different regions. The breakdown voltage has an evident positive shift under the strain of Region-GD. It is claimed that increased strain in the AlGaN layer causes increasing density of 2DEG. In turn, it decreases the electric field locally[20], hence enhance the off-state breakdown voltage. And  $V_{br}$  can be improved by 12% from 731V to 821V when the strained lattice constant  $a$  changes from 3.173061Å to 3.187229Å.

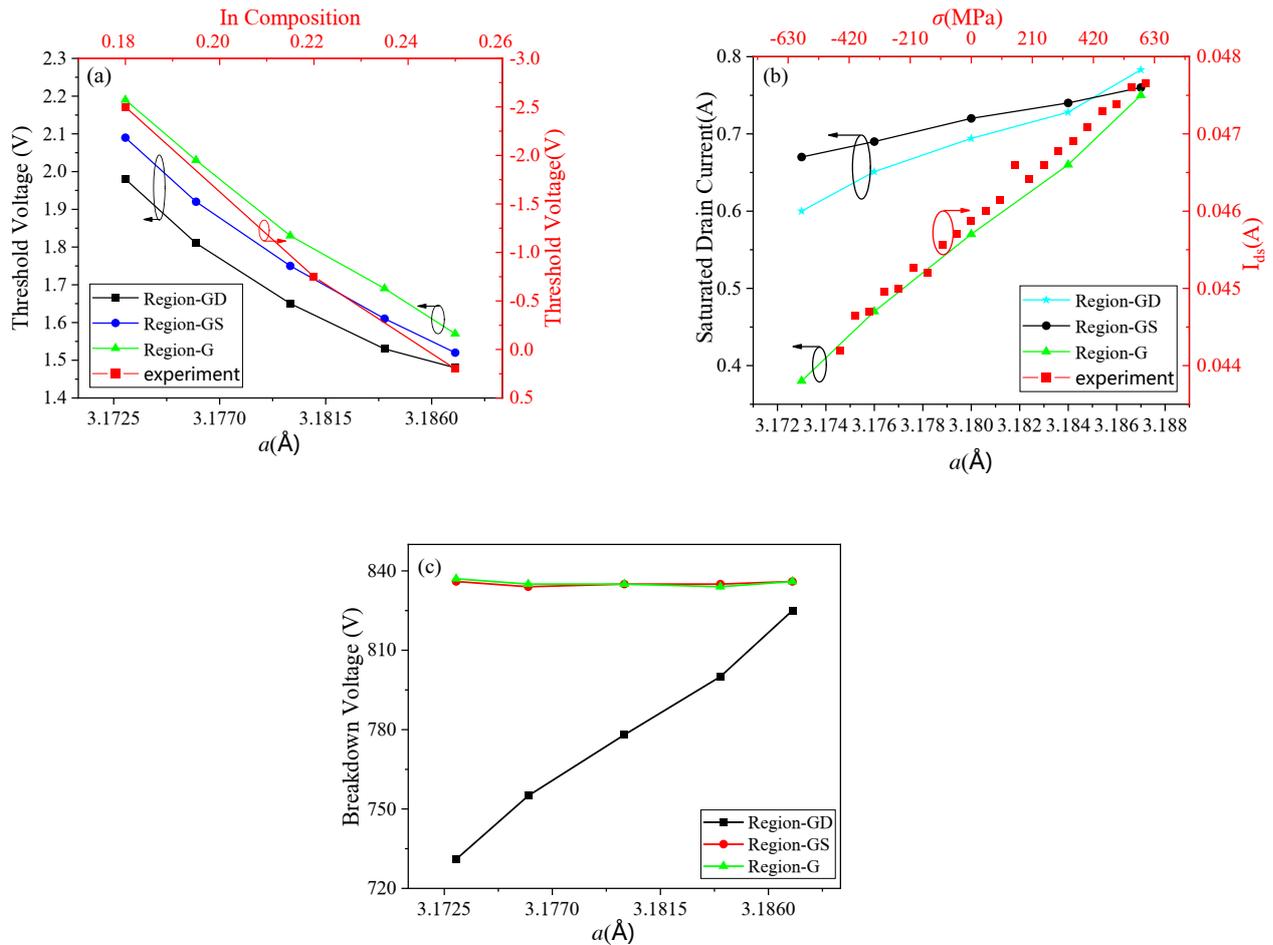


Fig. 4 (Color online) The relationship between the strained lattice constant  $a$  of Region-GS, Region-G and Region-GD in HEMT and the electrical features, compared to the experimental data [16][17]: (a) the threshold voltage  $V_{th}$ , (b) the drain saturation current  $I_{sat}$ , and (c) the breakdown voltage  $V_{br}$

## 4 Conclusion

In this paper the influence of inhomogeneous biaxial strain in barrier on electrical characteristics of normally-off HEMT with p-GaN gate have been numerically explored. The simulation results indicate that strain on the AlGaN barrier layer has a significant impact on the electrical characteristics of the HEMT device. In Region-G or gate region, the strain has the most predominant impact on  $V_{br}$  with a decreasing of 39%, while  $I_{sat}$  with an increasing of 97% as the  $a$  increases from 3.173061Å to 3.187229Å. In addition, the  $V_{br}$  can be improved with 12% by strain between the gate and drain electrode or

Region-GD when the increases. The built model and results can pave the way for optimizing the performance and improving the reliability of the under developing normally-off HEMTs. should be centred and should be numbered with the number on the right-hand side.

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