Source-Drain Punch-Through Analysis of High Voltage Off-State AlGaN/GaN HEMT Breakdown

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Abstract. AlGaN/GaN high-electron mobility transistor’s (HEMT’s) off-state breakdown is investigated using conventional three-terminal off-state breakdown I–V measurement. Competition between gate leakage and source-injection buffer leakage (SIBL) is discussed in detail. It is found that the breakdown is dominated by source-injection which is sensitive to gate voltage and gate length at large gate-to-drain spacing (Lgd > 7μm), where a threshold drain voltage of the occurrence of the SIBL current in GaN buffer exists, and after this threshold voltage the SIBL current continually increased till the buffer breakdown. Our analysis showed that due to the punch-through effect in the buffer, a potential barrier between 2DEG and GaN buffer at the source side mainly controlled by the drain voltage determines the buffer leakage current and the occurrence of the following buffer breakdown, which could explain the experimentally observed breakdown phenomenon.

1. Introduction

The AlGaN/GaN high electron mobility transistors (HEMTs) are considered to be promising candidates for the next generation high power and high frequency devices, due to their outstanding fundamental physical properties, such as large breakdown fields, low on-state resistance and high electron mobility [1]-[3]. One of the major issues that limit the performance of AlGaN/GaN HEMTs is the off-state breakdown voltage (VBRoff), because it determines the maximum working voltage and output power. It is well known that GaN buffer layer has a large density of deep-level acceptor traps originated from dislocations, defects unintentionally or intentionally introduced by the epi-growth, which can result in high-resistance buffer to enhance device performance, for example, prevents punch-through and buffer leakage current [4][5].

In this work, AlGaN/GaN HEMT’s off-state breakdown is investigated by conventional three-terminal off-state breakdown I–V measurement. Competition between gate leakage and the source-injection buffer leakage [6] (SIBL) breakdown mechanisms is discussed.

2. Device fabrication

The AlGaN/GaN HEMT structure in this work was grown on a [0001] polished sapphire substrate by MOVCD. As shown in Fig. 1, a 2 μm unintentionally doped GaN channel layer, a 2 nm AlN nucleation layer and a 22 nm unintentionally doped Al₀.₃Ga₀.₇N were grown on the substrate from bottom to up one
by one. From room temperature Hall measurements, it could be seen that at the AlGaN/GaN interface, the 2DEG density is $1.2 \times 10^{13}$ cm$^{-2}$ and the electron mobility is 1159 cm$^2$/Vs.

A complete AlGaN/GaN HEMT process flow in this paper contains source/drain ohmic contact formation, mesa isolation etching, gate Schottky contact, passivation and contact via etching. The source/drain ohmic contact was formed by evaporating Ti/Al/Ni/Au and then annealing at 830 °C for 30 seconds under N$_2$ atmosphere. The mesa isolation was performed by RIE. The Schottky contact came from e-beam evaporated Ni/Au layer. And a 200 nm SiN layer was deposited as passivation material.

3. Experiment results

The output and transfer characteristics of a fabricated AlGaN/GaN HEMT with $L_g=1 \ \mu m$, $L_{gs}=1 \ \mu m$ and $L_{gd}=1 \ \mu m$ showed that the saturation drain current density could reach 0.75A/mm@$V_g=2V$, the gate threshold voltage, $V_{th}$, is -3.5V and the maximum transconductance is 136mS/mm, which were used for verification of the following simulation of AlGaN/GaN HEMT.

The conventional three-terminal off-state breakdown I-V measurement was adopted to characterize high-voltage performance of the AlGaN/GaN HEMT with different Lgd, where the breakdown voltage, $V_{BR}$, is defined as the drain voltage at which the drain current reaches 1mA/mm with $V_g < V_{th}$. The comparison of gate current, $I_g$, and source current, $I_s$, for devices with different Lgd at $V_{gs}=-7V$ and $V_s=0V$ is shown in Fig. 2(a). It is obviously shown that there are different breakdown mechanisms for devices with different Lgd. For gate-to-drain spacing $L_{gd} \leq 7\mu m$, gate current, $I_g$, is the major part of the drain current, $I_d$, and the device breakdown originates from $I_g$. However, for larger Lgd, $I_g$ is very small and $I_s$ dominates $I_d$, the leakage current path is inside GaN buffer instead of barrier layer between the gate and drain. Due to interests in high voltage (>300V) breakdown, our main analysis focussed on the buffer off-state breakdown.

![Figure 1. Cross-section of AlGaN/GaN HEMT](image)

![Figure 2. Gate and source currents by three-terminal off-state breakdown measurements at $V_g = -7V$ and $V_s = 0V$ for HEMT with $L_g = 3\mu m$, $L_{gs} = 1\mu m$, $W = 50\mu m$ and different $L_{gd}$ in (a) linear and (b) logarithmic coordinate.](image)
For device with larger $L_{gd}$ (>7μm), Figure 2(a) shows that the source current should determine the device breakdown when $V_d > 150V$. Figure 2(b) shows that for device with $L_{gd}=13 \mu m$, $I_g$ dominate $I_d$ when $V_{ds}<150V$ and $I_s$ becomes the major part of $I_d$ when $V_{ds}>150V$ till the occurrence of device breakdown. The above experimental results suggest that there exists a buffer current driven device breakdown.

4. Simulation and analysis
Simulation models for the same device structures as the samples of AlGaN/GaN HEMT were established based on Sentaurus TCAD, where all model parameters were extracted and verified by the experimental data. Since the source-drain buffer current is the focus of this work, the gate leakage is excluded from the model. The simulated 2D electron density distribution at different $V_{ds}$ is given in Fig. 3, which shows the existence of a SIBL current path in GaN buffer layer, induced by the large positive drain voltage. With the increasing drain voltage, the SIBL path is gradually approaching 2DEG channel at the source side through GaN buffer from 2DEG channel at the drain side, and then the source-drain punch-through occurs. When $V_{ds}=160V$, the current path could be obviously observed.

Figure 3. Simulated electron density distribution at different $V_{ds}$ ($L_g = 3 \mu m$, $L_{gd} = 5 \mu m$, $V_g = -7V$, $V_s = 0V$).

Moreover, the simulated distribution of the bottom of conduction band is given in Figure 4, which shows the significant decrease of the potential barrier occurs for source-injected electrons from 2DEG channel at source side after large drain voltage is applied. It was found that as the drain voltage increasing, the minimum barrier height along the SIBL path is lowered, while the barrier position moved close to the source terminal and the AlGaN/GaN interface.

Figure 4. Simulated distribution of bottom of conduction band at $V_{ds} = 240V$
In order to accurately characterize the electron barrier in GaN buffer, the heights and positions of minimum electron barrier are quantitatively extracted under different drain voltages, shown in Fig. 5(a) and (b). As the drain voltage increasing, the barrier position is moving close to the source terminal and the AlGaN/GaN interface (Fig. 5(a)), while the barrier height is lowering (Fig. 5(b)). It should be noted that, the minimum potential barrier approaches a saturated value, 0.2eV, while the corresponding positions of minimum potential barrier move close to below 0.2µm from AlGaN/GaN interface, which indicates the electron in 2DEG channel could easily inject into the GaN buffer. The above physical description could explain that Is starts to dominate Id when Vds = 150V in Figure 2(b), at which the minimum potential barrier become low enough for electrons to inject into GaN buffer.

5. Conclusion
The off-state breakdown mechanisms of AlGaN/GaN HEMTs with different Lgd are investigated. Our experimental results showed that the breakdown is dominated by source-injection for devices with large gate-to-drain spacing (Lgd > 7µm), where a threshold drain voltage (about 150V) exists, above which the SIBL current continually increases till the occurrence of breakdown. The following theoretical analysis based on Sentaurus TCAD simulation showed the existence of a current path in GaN buffer layer, mainly induced by the large positive drain voltage. With the increasing drain voltage, the SIBL path gradually approaches 2DEG channel at the source side from 2DEG channel at the drain side, while the minimum potential barrier between the 2DEG and GaN buffer at source side decreases until electrons in the source-side 2DEG channel could inject into the buffer, which finally results in the subsequent buffer breakdown.

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