

Etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs with high output current and breakdown voltage (>600 V)

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By etching the AlGaN layer close to the gate edge of the drain side, the novel AlGaN/GaN high-electron-mobility transistor with the etched AlGaN epitaxial layer (etched AlGaN/GaN high-electron-mobility transistors, HEMTs) is proposed in this work with the high-resistance GaN buffer layer. The relationship between the 2D electron gas (2DEG) concentration and the thickness of the AlGaN layer has been explored. The 2DEG density under the etched barrier is reduced to optimise the surface electric field and mobility of 2DEG. The electric field is reshaped by the etched AlGaN layer, featuring an extra electric field peak far away from the gate edge. The electric field peak near the gate is decreased effectively because of the extra electric field peak, which therefore improves the breakdown voltage (BV). The mobility of 2DEG is increased because of the low 2DEG concentration, which improves the output current (I_{DS}). The experimental BV is improved from 152 V for the conventional structure to 620 V for etched AlGaN/GaN HEMTs because of the optimised surface electric field. The maximum output current (I_{max}) is increased from 381 to 478 mA/mm. The trade-off between the BV and $R_{\text{on,sp}}$ has been improved to break the silicon limit. It is concluded that the gate-edge etching technique can significantly increase both BV and I_{DS} for AlGaN/GaN HEMTs.

1. Introduction: The power devices with the GaN material are the core of the next generation power system owing to their high performance [1]. The studies on AlGaN/GaN high-electron-mobility transistors (HEMTs) are mainly focused on improving the breakdown voltage (BV), reducing the specific on-resistance ($R_{\text{on,sp}}$) by optimising the electric field distribution [2], suppressing the current collapse with new structures [3], and improving the device reliability [4]. Many techniques have been applied previously to improve the BV for the silicon power devices [5–8]. However, these techniques cannot be directly transplanted to AlGaN/GaN HEMTs because of the special breakdown mechanism of HEMTs [8]. In [9, 10], the relationship between the concentration of two-dimensional electron gas (2DEG) and the thickness for the AlGaN epitaxial layer are reported, which indicates that the 2DEG concentration is increased and saturated when the thickness of the AlGaN epitaxial layer is increased gradually.

To reduce the electric field near the gate edge, a new AlGaN/GaN HEMTs with the etched AlGaN epitaxial layer (etched AlGaN/GaN HEMTs) is designed, which applies the discipline of 2DEG concentration varying with the thickness of the AlGaN epitaxial layer [9, 10]. The 2DEG density is modulated by the etched AlGaN layer where the 2DEG density is lower compared with the other unetched region. This method is similar to the lightly doped drain technology for complementary metal-oxide-semiconductor. The gate-etch etching, which is capable of optimising the electric field distribution as well, can be viewed as an alternative to the field-plating technology. However, the additional capacitance would be introduced in the filed-plating technology, which is detrimental to the switching characteristics. In the etched AlGaN/GaN HEMTs, a new electric field peak is introduced at the drain-side edge of the trench, which reduces the high electric field near the gate-side edge of the trench. As a result, the BV is improved compared to the AlGaN/GaN HEMTs without gate-edge etching. The simulated BV of 466 V for the conventional $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs is increased to 640 V for the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs. The experimental BV is 620 V for the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs compared with the 152 V for the conventional $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs. The mobility of 2DEG is increased

because of the low 2DEG concentration, which results from the relationship between the 2DEG concentration and mobility [11, 12]. However, the output current (I_{DS}) is improved because the large increase in mobility is compensated by the slight decrease in 2DEG concentration. The maximum output current (I_{max}) is increased from 381 mA/mm (conventional $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs) to 478 mA/mm (etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs).

2. Device structure and description: The schematic diagram of the proposed etched AlGaN/GaN HEMTs is shown in Fig. 1. The high-density 2DEG is introduced by the polarisation effect of the AlGaN/GaN heterojunction. The concentration of 2DEG is improved with the increased thickness of the AlGaN epitaxial layer [9, 10]. To reduce the 2DEG density near the gate, the AlGaN layer near the gate is etched to form a barrier step in the etched AlGaN/GaN HEMTs compared with the conventional AlGaN/GaN HEMTs. In the off state of the AlGaN/GaN HEMTs, the low 2DEG density is depleted easily to expand the depletion region and decrease the high electric field near the gate. The high electric field peak near the gate is reduced effectively because of the new electric field peak introduced by the etched AlGaN layer, which improves the BV of the etched AlGaN/GaN HEMTs. Moreover, the mobility of the 2DEG is increased owing to the low 2DEG concentration [11, 12], which improves the I_{DS} in the on state of AlGaN/GaN HEMTs simultaneously. In this Letter, the etched AlGaN/GaN HEMTs is verified by the simulation and experimental results. The AlGaN/GaN HEMTs has the undoped AlGaN barrier and i-GaN buffer layer along the (0001) direction of Ga-face. Al constituent for the Etched AlGaN/GaN HEMTs is 32%. The total thickness of the AlGaN epitaxial layer is 20 nm. The thickness of the GaN buffer layer with the high resistance GaN buffer layer is 1.8 μm . The length of the drift region is represented by L_{D} . The depth and length of the etched AlGaN are modulated by H and D .

3. Results and discussion: Fig. 2 shows the surface electric field distribution for $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs. The surface electric field is located at the interface of the AlGaN/GaN heterojunction. It can be seen in Fig. 2a that a new electric field peak is

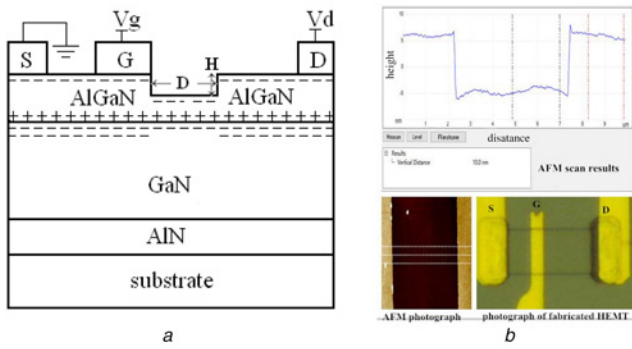


Fig. 1 Etched AlGaIn/GaN HEMTs
a Schematic diagram
b AFM scan results

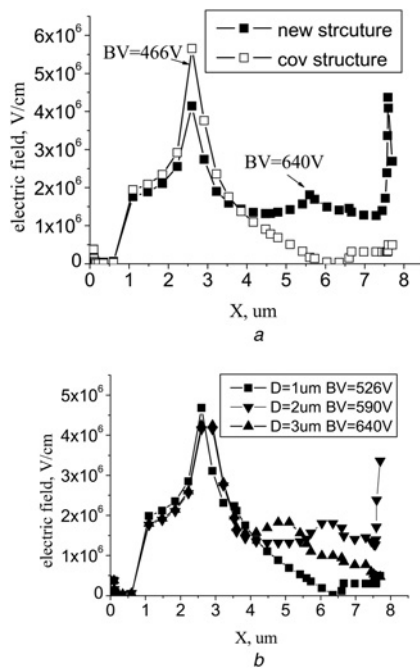


Fig. 2 Surface electric field distributions of $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs
a Conventional and etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs
b Etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs with the different D : $H=10$ nm, $L_D=5$ μm

introduced to reduce the high electric field near the gate by the etched AlGaIn layer. The 2DEG is depleted completely in the etched AlGaIn/GaN HEMTs to bear the high-simulated BV of 640 V. For the conventional AlGaIn/GaN HEMTs, the 2DEG cannot be depleted completely from the gate-to-drain electrodes because of the high-density 2DEG distribution. The surface electric field is triangular, and the high electric field peak is located near the gate, which is not conducive to obtain the high BV and high reliability for AlGaIn/GaN HEMTs. The 2DEG density is decreased near the gate for the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs by the etched AlGaIn layer. The high electric field near the gate is reduced effectively because of the new electric field peak, which increases the simulated BV from 466 V for the conventional structure to 640 V for the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs. Fig. 2b shows the variation of the surface electric field with the parameter D for the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs. It can be seen in Fig. 2b that the high electric field near the gate is reduced gradually when the etched AlGaIn epitaxial layer increases. When D is 2 μm and L_D is 5 μm , the 2DEG and the GaN buffer layer are depleted

completely. The simulated BV reaches 590 V for the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs. When D is 3 μm , the high electric field peak is introduced near the drain. The simulated BV for the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs is increased to 640 V by further lowering the high electric field peak near the gate edge.

In contrast to the conventional AlGaIn/GaN HEMTs, the proposed etched AlGaIn/GaN HEMTs is fabricated with one additional AlGaIn layer etching process. First, a device mesa is formed using a Cl_2/He plasma dry etching in an inductively coupled plasma reactive ion etching (ICP-RIE) system, followed by the source/drain ohmic contact formation with Ti/Al/Ni/Au annealed at 850°C for 30 s. The ohmic contact resistance is measured to be 0.85 $\Omega\cdot\text{mm}$. Ni/Au e-beam evaporation and liftoff were carried out subsequently to form the gate electrodes. Subsequently, the windows of the etched AlGaIn region are defined (Fig. 1) by photolithography, and the second ICP is applied to form the etched AlGaIn layer near the gate with H equal to 10 nm. Subsequently, the sample is annealed at 450°C for 10 min.

Fig. 3 shows the characteristic curves for the conventional and etched depletion mode $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs when the devices are turned off. It can be seen that the experimental BV of Etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs is improved because the high electric field has been decreased near the gate edge thank to the new electric field peak near the etched AlGaIn. The BV of etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs increases with the length of the etched AlGaIn. When D is 7 μm and L_D is 10 μm , the BV is improved to 620 V, which has increased by 308% compared with the conventional $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs with the BV of 152 V. In [13], the BV of etched $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMTs had been improved only by 58% compared with the conventional $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ HEMTs due to the leakage current of the GaN buffer layer. The high BV of 620 V for etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs can be obtained compared with 152 V in the conventional $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs, which also benefits from the high resistance of the GaN buffer layer. For AlGaIn/GaN HEMTs, the breakdown can be occurred resulting from two factors. The first is the avalanche formed by the collision ionisation at the high electric field area, which needs the high resistance of the GaN buffer layer. The second breakdown is caused by the leakage current of the GaN buffer layer with a certain resistance.

Fig. 4 plots the dc and pulsed current–voltage (I – V) characteristics of the conventional and etched depletion mode $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs with the various D . The output current of I_{DS} is increased for the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs resulting from the improved mobility by the low 2DEG density compared with the conventional $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs. For the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs, I_{DS} increases with the increasing D . The I_{max} of the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs is improved to 478 mA/mm compared with the

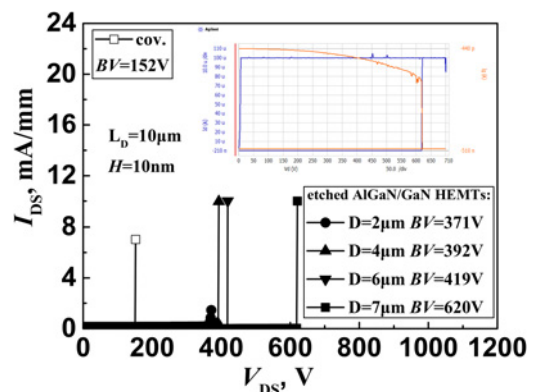


Fig. 3 Experimental breakdown characteristics of the conventional and etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs

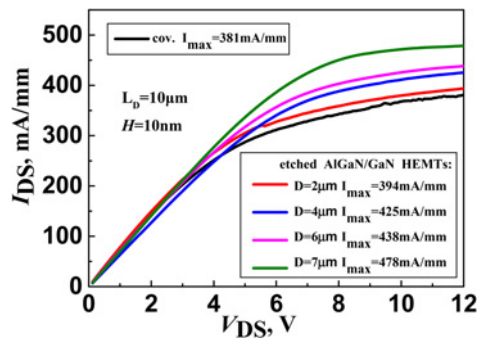


Fig. 4 DC and pulsed I - V characteristics of the conventional and etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs: $V_{gs} = 2$ V

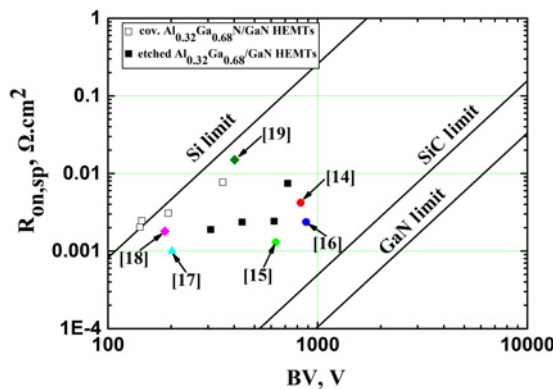


Fig. 5 $R_{on,sp}$ versus BV with the ideal silicon, SiC and GaN limits, the reported structure and proposed etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs

conventional $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs of 381 mA/mm. The phenomenon of I_{DS} increased has not been found in [13].

The $R_{on,sp}$ of etched and conventional $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs versus BV are compared in Fig. 5 with the silicon, SiC and GaN limits. The comparison demonstrates the performance of the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs is superior to the conventional $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs, and the silicon limit has been broken. The results of etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ are closer to the SiC limit, which is the goal to improve the power GaN devices. The reported results in [14–19] have also been shown in Fig. 5. The high BV and I_{max} can be obtained simultaneously for etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ due to the decreased electric field peak near the gate and increased mobility of 2DEG. However, the BV has been improved only in [13, 20].

4. Conclusion: To optimise the surface electric field and improve the BV for AlGaN/GaN HEMTs, a new AlGaN/GaN HEMTs is proposed with the etched AlGaN epitaxial layer in this Letter. The 2DEG density is modulated by the etching of the AlGaN epitaxial layer, which applies the fact that the 2DEG concentration varies with the AlGaN hetero-epitaxial layer thickness. The low-density 2DEG is formed near the gate to improve the performance of AlGaN/GaN HEMTs in both the off state and the on state. The new electric field peak is introduced near the etched AlGaN epitaxial layer because of the low 2DEG concentration in the off state, which effectively reduces the high electric field near the gate to improve the BV . The experimental BV of 620 V for etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs is obtained compared with 152 V for the conventional $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs. The mobility of the etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs is increased because of the relationship of the 2DEG concentration and mobility for the AlGaN/GaN heterojunction.

The output current is improved resulting from the increased mobility, which compensates the decreased 2DEG concentration. The I_{max} is increased from 381 mA/mm (conventional $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs) to 478 mA/mm (etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ HEMTs). The trade-off between the BV and $R_{on,sp}$ has been improved to break the silicon limit. The results of BV and $R_{on,sp}$ for etched $\text{Al}_{0.32}\text{Ga}_{0.68}\text{N}/\text{GaN}$ are closer to the SiC and GaN limits, which is the goal to improve the power GaN devices. Although the depletion mode AlGaN/GaN HEMTs is discussed in this Letter, this idea can also be applied to the enhancement mode AlGaN/GaN HEMTs with the etched AlGaN epitaxial layer.

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6 References

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