AlGaN/GaN HEMTs With Low Leakage Current and High On/Off Current Ratio
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Abstract—In this letter, we propose using an oxide-filled isolation structure followed by \( \text{N}_2/\text{H}_2 \) postgate annealing to reduce the leakage current in AlGaN/GaN HEMTs. An OFF-state drain leakage current that is smaller than \( 10 \times 10^{-9} \text{ A/mm} \) (minimum \( 5.1 \times 10^{-10} \text{ A/mm} \)) can be achieved, and a gate leakage current in the range of \( 7.8 \times 10^{-10} \) to \( 9.2 \times 10^{-11} \text{ A/mm} \) (\( V_{\text{GS}} \) from \(-10 \) to \( 0 \) V and \( V_{\text{DS}} = 10 \) V) is obtained. The substantially reduced leakage current results in an excellent ON/OFF current ratio that is up to \( 1.5 \times 10^8 \). An improved flicker noise characteristic is also observed in the oxide-filled devices compared with that in the traditional mesa-isolated GaN HEMTs.

Index Terms—Flicker noise, GaN, HEMTs, leakage current.

I. INTRODUCTION

HIGH-PERFORMANCE AlGaN/GaN HEMTs have been successfully demonstrated for various applications in recent years [1], [2]. One of the critical issues that still remain for GaN HEMTs is the leakage current which causes additional noise source [3], current collapse effect [4], and reliability problems [5]. Experimental results also indicate that a leakage current results in a lowered breakdown voltage due to the hot-carrier-induced impact ionization [6]. The leakage current was also reported to increase the OFF-state loss and reduce the power supply efficiency [7].

Different approaches were proposed to reduce the gate leakage current [8]–[12]. One straightforward solution was to add an additional gate dielectric layer (MIS-HEMT structure) to block the leakage current path [8]–[10]. A gate leakage current that is as low as \( 10^{-9} \text{ A/mm} \) was reported [8], while the transconductance was relatively low due to the reduced channel control capability [10]. In addition, fluoride or \( \text{O}_2 \) plasma treatments were employed to reduce the gate leakage current [11], [12], and a leakage current in the range of \( 10^{-5} \) to \( 10^{-8} \text{ A/mm} \) was achieved. Different studies were also conducted to investigate the origins of the leakage current [13], [14].

In this letter, we propose a method using the oxide-filled mesa region followed by postgate annealing under a \( \text{N}_2/\text{H}_2 \) mixture ambient to reduce the transistor leakage current. Previous studies reported that the etching process for mesa isolation in GaN-based devices produced deep level traps, causing an increased leakage current [15], [16]. It was found that the defect charges around the gate finger could result in barrier narrowing in the AlGaN cap layer, leading to increased gate leakage current [6]. It was also reported that the OFF-state leakage current can be improved if the gate Schottky contacts are not directly affected by the mesa region [17]. With the proposed oxide-filled structure, the surface states and traps around the mesa edge can effectively be eliminated. Compared with the conventional mesa-isolated structure, the gate finger tips across the trap-rich mesa edge can also be prevented. Moreover, the postgate annealing treatment with forming gas further reduces the traps by hydrogen passivation. The measured results demonstrate a substantially reduced gate and drain leakage current and an extremely high ON/OFF drain current ratio in the proposed oxide-filled GaN HEMTs.

II. DEVICE DESIGN AND FABRICATION

Fig. 1(a) and (b) shows the cross sections of the AlGaN/GaN HEMTs using the traditional mesa isolation and the proposed oxide-filled isolation structures, respectively. The device structure was grown on a c-plane sapphire substrate by metal–organic chemical vapor deposition, which consisted of a GaN buffer layer, a 3-\( \mu \text{m} \) undoped GaN layer, a 3-nm undoped AlGaN layer, a 20-nm n-doped AlGaN barrier layer (25% Al composition), and, finally, a 5-nm undoped AlGaN cap layer. The source/drain ohmic contacts were first formed by Ti/Al/Ti/Au deposition using rapid thermal annealing at 800 °C for 30 s in a \( \text{N}_2 \) ambient. After making the ohmic contact, a mesa isolation process was arranged by Editor J. A. del Alamo. The authors are with the Department of Electrical Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan (e-mail: d925060@oz.nthu.edu.tw; g9663509@oz.nthu.edu.tw; shshu@ee.nthu.edu.tw).

Fig. 1. AlGaN/GaN HEMTs. (a) Mesa isolation structure. (b) Oxide-filled isolation structure.
treatment at 350 °C for 60 s in a N$_2$/H$_2$ ambient. Finally, a PECVD Si$_3$N$_4$/SiO$_2$ layer of 0.4 μm/0.8 μm was deposited for surface passivation. Note that the reference design with the conventional mesa isolation had identical process steps except for surface passivation. Note that the threshold voltage shifting toward a more negative value is observed in the oxide-filled devices. Similar trends were observed for the devices after surface passivation and explained by the reduced donorlike traps [20]. With the oxide-filled process, the traps at the mesa edge particularly underneath the Schottky gate are reduced, and a similar explanation can be applied.

As for the leakage characteristics, the devices with oxide-filled isolation demonstrate an extremely low OFF-state leakage current ($I_D < 1.0 \times 10^{-9} \text{ A/mm}$; minimum $5.1 \times 10^{-10} \text{ A/mm}$ at $V_{GS} = -5.4 \text{ V}$) and an excellent ON/OFF current ratio that is up to $1.5 \times 10^8$ (a standard deviation of 22%). Even for the conventional mesa-isolated HEMTs, the OFF-state $I_D$ is smaller than $2.1 \times 10^{-8} \text{ A/mm}$ (minimum $3.2 \times 10^{-9} \text{ A/mm}$ at $V_{GS} = -4.6 \text{ V}$), and a ratio that is up to $3.5 \times 10^7$ can be obtained (a standard deviation of 24%), which is greatly improved compared with that reported for traditional GaN HEMTs without the proposed forming gas treatment (typical OFF-state $I_D \sim 10^{-4}$ to $10^{-6} \text{ A/mm}$; see sample_R1, R2, [18], and [19]). It can be seen that postgate annealing reduces the leakage current by more than three orders of magnitude. With the additional oxide-filled process, the leakage current is further improved by another one to two orders of magnitude. Note that the threshold voltage shifting toward a more negative value is observed in the oxide-filled devices. Similar trends were observed for the devices after surface passivation and explained by the reduced donorlike traps [20]. With the oxide-filled process, the traps at the mesa edge particularly underneath the Schottky gate are reduced, and a similar explanation can be applied.

**III. RESULTS AND DISCUSSION**

Fig. 2(a) shows the $I_D$–$V_{GS}$ characteristics, where five typical devices are averaged to show a more statistical result. The results from our previous studies with identical process steps and similar material layers except the oxide-filled isolation and postgate annealing are also presented for comparison (sample_R1 and sample_R2). Some performance figures of the devices shown in Fig. 2(a) are as follows. The $I_{D,max}$ (under $V_G = 0 \text{ V}$ and $V_D = 10 \text{ V}$) are $115 \text{ mA/mm}$ (sample_R1), $144 \text{ mA/mm}$ (sample_R2), $80 \text{ mA/mm}$ (oxide filled), and $114 \text{ mA/mm}$ (mesa isolated). The corresponding $g_{mpk}$ (peak transconductance) are $36, 77, 30, \text{ and } 42 \text{ mS/mm}$, respectively, and the values of the source resistance $R_s$ are $13.3, 9.2, 16.6, \text{ and } 13.2 \text{ Ω/mm}$, respectively. The threshold voltages of the R1, R2, oxide-filled, and mesa-isolated devices are $-4.8, -3.3, -5.1, \text{ and } -4.6 \text{ V}$, respectively.
current spectral densities $S_{de}/I_D^2$ of both device structures in the linear region ($V_{GS} = 0$ V and $V_{DS} = 0.1$ V). The result clearly indicates that the oxide-filled design presents a lower noise level compared with the traditional mesa-isolated device. Since flicker noise is related to the defects in the devices, the results also indicate that the oxide-filled isolation design is effective to mitigate the trapping effect in GaN HEMTs.

The fundamental ideas of oxide filled and postgate annealing are somewhat different, and yet, both of them can reduce the leakage current. The oxide-filled process levels the gate finger tips with the mesa to avoid the trap-rich mesa edge. On the other hand, the postgate annealing process can recover the damaged surface area by hydrogen diffusion [21], [22]. Since the etching damage is more severe in the mesa-edge region, it is relatively more difficult to be recovered by hydrogen diffusion. With the oxide-filled process, the mesa edge is filled up, and this problem can be prevented, and thus, an extremely low leaking level can be observed. If the devices are treated only with the oxide-filled process, the mesa-edge traps can be avoided, whereas the traps in the rest of the active area are still a problem. For the devices with oxide-filled isolation followed by postgate annealing, hydrogen diffusion at the mesa edge may not be as effective. However, as explained earlier, it is not that critical anymore. The results suggest that both the oxide-refilled design and the forming gas treatment are important factors to the observed low leakage current and the reduced trapping effect.

### IV. Conclusion

In this letter, we have proposed an oxide-filled isolation structure followed by postgate annealing to alleviate the trapping effect and reduce the leakage current in GaN HEMTs. The devices showed the leakage current level to be as low as $10^{-9}$ A/mm, which was about three orders of magnitude smaller than the typical reported values. An extremely high ON/OFF current ratio that is up to $1.5 \times 10^8$ was obtained. The reduced flicker noise level in the oxide-filled GaN HEMTs also indicated alleviated trapping effects, which was consistent with the observed low leakage current.

### References


