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Unidirectional p-GaN gate HEMT with composite source-drain field plates

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Dear editor,

GaN-on-Si high electron mobility transistors (HEMTs) have attracted attention for power device applications due to their low cost and large-area availability [1]. Recently, bidirectional switches are highly desirable in many industrial bidirectional power conversion applications, such as rolling mills, elevators, and wind power generation. In addition, normally-off unidirectional HEMTs can be valuable devices to implement the high-performance bidirectional switches [2, 3].

Usually, normally-off unidirectional HEMTs are realized by a Schottky barrier diode (SBD) embedded in the drain electrode in HEMTs. Techniques using fluorine implantation or metal oxide semiconductors have been employed. However, the p-GaN gate technique [4] with good controllability and stability in threshold voltage (V_{th}) has not been reported in normally-off unidirectional HEMTs. Besides, recessed SBD [5] and field-plate techniques [6] can provide relevant references in unidirectional HEMTs with small turn-on voltage (V_{on}), high breakdown voltage (BV), and good dynamic performance.

In this study, a unidirectional p-GaN HEMT with recessed Schottky drain and composite source-drain field plates (RS-FP-HEMT) is experimentally demonstrated. The influence of drain voltage stress on the dynamic performance is investigated and revealed.

Experiment. Figures 1(a) and (b) show the schematic cross-sectional structures of the conventional p-GaN HEMT with ohmic drain (C-HEMT) and proposed RS-FP-HEMT, respectively. Both devices were fabricated on a GaN-on-Si wafer. The epitaxial structure consists of a 3.4 μm buffer layer, 320 nm i-GaN channel layer, 0.7 nm AlN interlayer, 15 nm $\mathrm{Al_{0.2}Ga_{0.8}N}$ barrier layer, and 75 nm p-GaN layer with Mg doping concentration of 1×10^{19} $\mathrm{cm^{-3}}$.

Device fabrication started with the formation of p-GaN gate island by reactive ion etching (RIE). Then, Ti/Al/Ni/Au metal stack was evaporated and annealed at 850°C for 30 s in N_2 ambient. The recessed Schottky drain was formed by a low damage RIE process, and the depth is ~25 nm. Afterward, the BOE treatment and annealing at 450°C in N_2 ambient were implemented [5]. The gate and drain metal were simultaneously deposited by sputtering W. Subsequently, 250 nm $\mathrm{Si_3N_4}$ and 400 nm $\mathrm{SiO_2}$ were deposited by plasma-enhanced chemical vapor deposition for surface passivation. Ni/Au metal stack was formed as the composite source-drain field plates. C-HEMT was also fabricated on the same wafer for reference. Both devices had a 2 μm source-gate spacing (L_{GS}), 4 μm p-GaN gate length (L_{G}), 20 μm gate-drain spacing (L_{GD}), and 5 μm source field plate length (L_{SFP}). In RS-FP-HEMT, the extended length over the barrier region (L_{EX}) of recessed Schottky drain and the length of drain field plate (L_{DFP}) were both 2.5 μm.

Results and discussion. In Figure 1(c), both devices showed the same V_{th} of 2.1 V at $I_{\mathrm{D}} = 1$ mA/mm. A low V_{on} of 0.36 V (at $I_{\mathrm{D}} = 1$ mA/mm) was achieved by low work function W in RS-FP-HEMT. In addition, the differential on-resistance (R_{on}) of 49 Ω·mm in RS-FP-HEMT was close to that of C-HEMT (48.2 Ω·mm).

As shown in Figure 1(d). At 150°C, the V_{on} reduced to 0.3 V. The reverse leakage current increased from 0.4 μA/mm at room temperature to 11 μA/mm at 150°C.

In Figure 1(e), both devices exhibited a similar forward BV ($\mathrm{BV_F}$) of 772 V at 1 μA/mm. C-HEMT had no reverse blocking capability, whereas the RS-FP-HEMT obtained a reverse BV ($\mathrm{BV_R}$) of −769 V. Thus, a high $\mathrm{BV_R}$ could be achieved without sacrificing the V_{on} via field plate techniques, which could improve the tradeoff between V_{on} and $\mathrm{BV_R}$.

As shown in Figure 1(f), RS-FP-HEMT exhibited a higher V_{th}, lower V_{on}, and higher $\mathrm{BV_R}$ than other reported normally-off unidirectional GaN HEMTs on Si substrate.

In Figures 1(g) and (h), the sharp electric field peak crowded at the gate and drain edges in the case of without field plate. When composite source-drain field plates were introduced, the peak electric field was significantly suppressed. Besides, the wider electric field distribution and

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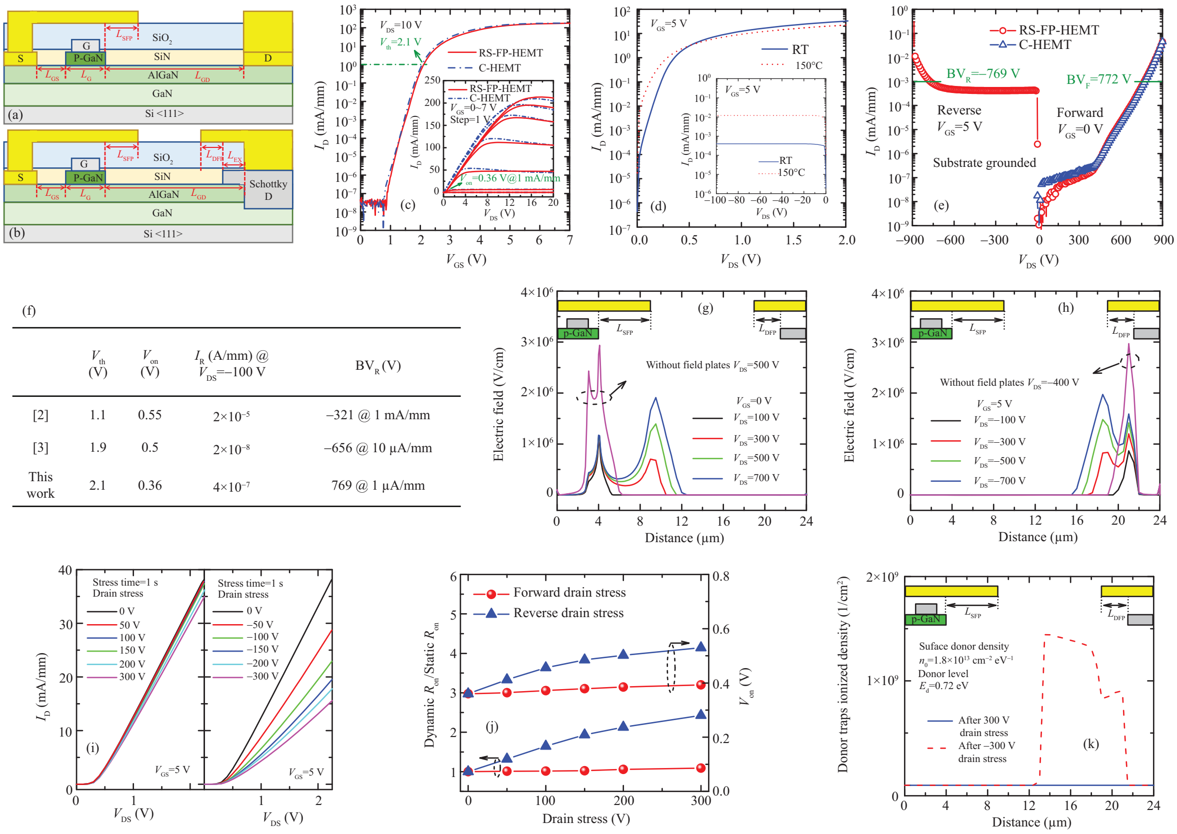

(f)

	V_{th} (V)	V_{on} (V)	I_R (A/mm) @ V_{DS}=−100 V	BV$_R$ (V)
[2]	1.1	0.55	2×10^{-5}	−321 @ 1 mA/mm
[3]	1.9	0.5	2×10^{-8}	−656 @ 10 μA/mm
This work	2.1	0.36	4×10^{-7}	769 @ 1 μA/mm

Figure 1 (Color online) (a) and (b) Schematic cross-section of the C-HEMT and RS-FP-HEMT; (c) transfer and output (the inset) characteristics; (d) forward and reverse (the inset) characteristics of the RS-FP-HEMT at room temperature and 150°C; (e) breakdown characteristics; (f) comparison between this work and other reported unidirectional HEMTs; (g) and (h) simulated electric field distribution in RS-FP-HEMT at different forward and reverse drain voltage; (i) forward I_D-V_{DS} characteristics of RS-FP-HEMT at different forward and reverse drain stresses; (j) the ratio of dynamic R_{on}/static R_{on} and V_{on} versus the drain stress; (k) the distribution of donor traps ionized density at Si_3N_4/AlGaN interface between gate and drain.

new electric field peak could be achieved by means of field plates at blocking state, indicating a high forward, and reverse blocking voltage in RS-FP-HEMT.

The impact of stress on the dynamic performance was shown in Figures 1 (i) and (j). The ratio (~1.1) of dynamic $R_{\rm on}$/static $R_{\rm on}$ and the shift of $V_{\rm on}$ (0.02 V) could be obtained at a forward drain stress of 300 V. The ratio of dynamic $R_{\rm on}$/static $R_{\rm on}$ was 2.4, and the shift of $V_{\rm on}$ was 0.17 V at a reverse drain stress of −300 V. Based on the simulations in Figure 1(k), the small dynamic ratio at forward drain stress could be attributed to the lower donor trap ionization density at the Si_3N_4/AlGaN interface, and the increase in the dynamic ratio at reverse drain stress might be due to the increased donor trap ionization because of electron injection into interface traps from drain edge.

Conclusion. We demonstrated a unidirectional p-GaN gate HEMT with a composite source-drain field plate. The device exhibited a low $V_{\rm on}$ of 0.36 V, $V_{\rm th}$ of 2.1 V, and BV$_{\rm F}$ and BV$_{\rm R}$ of >760 V. An excellent dynamic performance was achieved and revealed by simulations. These results could offer a significant reference to further improve the performance of unidirectional devices.

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References

1 Chen K J, Haberlen O, Lidow A, et al. GaN-on-Si power technology: devices and applications. IEEE Trans Electron Dev, 2017, 64: 779–795
2 Zhou C H, Chen W, Piner E L, et al. Schottky-ohmic drain AlGaN/GaN normally off HEMT with reverse drain blocking capability. IEEE Electron Device Lett, 2010, 31: 668–670
3 Lei J C, Wei J, Tang G F, et al. Reverse-blocking normally-off GaN double-channel MOS-HEMT with low reverse leakage current and low ON-state resistance. IEEE Electron Dev Lett, 2018, 39: 1003–1006
4 Uemoto Y, Hikita M, Ueno H, et al. Gate injection transistor (GIT)-a normally-off AlGaN/GaN power transistor using conductivity modulation. IEEE Trans Electron Dev, 2007, 54: 3393–3399
5 Zhang T, Zhang J C, Zhou H, et al. A>3 kV/2.94 m Ω·cm^2 and low leakage current with low turn-on voltage lateral GaN Schottky barrier diode on silicon substrate with anode engineering technique. IEEE Electron Dev Lett, 2019, 40: 1583–1586
6 Saito W, Nitta T, Kakiuchi Y, et al. Suppression of dynamic on-resistance increase and gate charge measurements in high-voltage GaN-HEMTs with optimized field-plate structure. IEEE Trans Electron Dev, 2007, 54: 1825–1830