AlGaN/GaN HEMTs on Silicon With Hybrid Schottky–Ohmic Drain for High Breakdown Voltage and Low Leakage Current

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***Abstract*—In this letter, a hybrid Schottky–ohmic drain structure is proposed for AlGaN/GaN high-electron-mobility transistors on a Si substrate. Without additional photomasks and extra process steps, the hybrid drain design forms a Γ-shaped electrode to smooth the electric field distribution at the drain side, which improves the breakdown voltage and lowers the leakage current. In addition, the hybrid drain provides an auxiliary current path and decreases the ON-resistance, in contrast to the devices with a pure Schottky drain. Compared with the conventional ohmic drain devices, the breakdown voltage could be improved up to 64.9%, and the leakage current is suppressed by one order of magnitude without degradation of the specific ON-resistance.**

***Index Terms*—Breakdown voltage, GaN, high-electron-mobility transistors (HEMTs), leakage current, Schottky, silicon.**

I. INTRODUCTION

HIGH-PERFORMANCE AlGaN/GaN high-electron-mobility transistors (HEMTs) have been realized on the silicon substrate for high-power applications in recent years, while one issue remains for these devices is the relatively high leakage current due to the quality of the buffer layer [1], [2]. Such a large leakage current causes serious OFF-state loss in the power supply and reduces the efficiency of the system. The breakdown mechanism is also affected by the leakage current through the buffer layer due to the imperfections and dislocations [3]. Different approaches such as Fe-doped [4] or C-doped buffer [5], thick buffer layer [6], substrate removal [7], and Schottky drain technology [8] were proposed to reduce the buffer leakage current and improve the breakdown voltage.

It has been proved that the process of ohmic contact is critical to the device buffer leakage current [9]. The metal spikes in the GaN channel layer and/or the buffer layer originating from alloyed ohmic contact formation cause undesired local electric field peaks at the drain side and induce leakage current. Recently, the Schottky drain approach for high-power AlGaN/GaN HEMTs has been proposed to enhance the buffer breakdown voltage [8]. However, the nonzero onset voltage V_{on} (typical $\sim$1 V) results in increased specific ON-resistance R_{on} [8], [10]. To overcome this problem, a hybrid Schottky–ohmic drain structure was proposed in E-mode AlGaN/GaN HEMTs [11]. Although also with the hybrid drain structure, the main purpose in [11] is to obtain reverse blocking capability for the normally off GaN HEMTs. In this letter, we use the hybrid drain that acts similar to a field plate to improve the OFF-state breakdown voltage and reduce the leakage current, while maintaining a similar R_{on}. In addition, the Schottky drain in [11] was treated by the fluorine plasma underneath, whereas the devices in this study do not use any fluorine treatment for the hybrid drain. Compared with the conventional ohmic drain devices, the hybrid drain devices in [11] showed a higher R_{on} and an almost unchanged breakdown voltage.

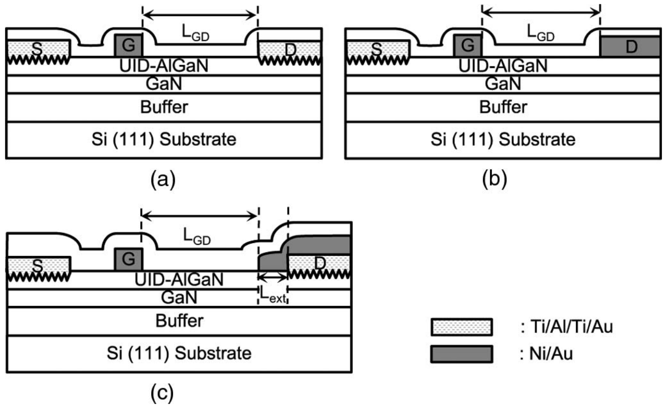

Fig. 1. Cross sections of AlGaN/GaN HEMTs on silicon with different types of drain electrodes: (a) ohmic drain, (b) Schottky drain, and (c) hybrid drain.

In this letter, we propose a hybrid Schottky–ohmic drain structure for AlGaN/GaN HEMTs on a Si substrate, which demonstrates a zero onset voltage and a similar specific ON-resistance with the traditional ohmic drain devices. Without any additional photomasks and process steps, the hybrid drain devices increase the breakdown voltage up to 64.9% and suppress the leakage current by about one order of magnitude without degradation of R_{on}.

II. DEVICE DESIGN AND FABRICATION

The cross sections of AlGaN/GaN HEMTs on a Si substrate with three different drain electrode structures including the conventional ohmic drain, pure Schottky drain, and the proposed hybrid Schottky–ohmic drain are shown in Fig. 1(a)–(c), respectively. In this letter, we compare the three device structures on two samples, i.e., sample A and sample B, with different epitaxial layer thicknesses ($\sim$1 μm for sample A and $\sim$4.8 μm for sample B). The layer structure of sample A consists of a 1-μm unintentionally doped (UID) layer (including buffer and

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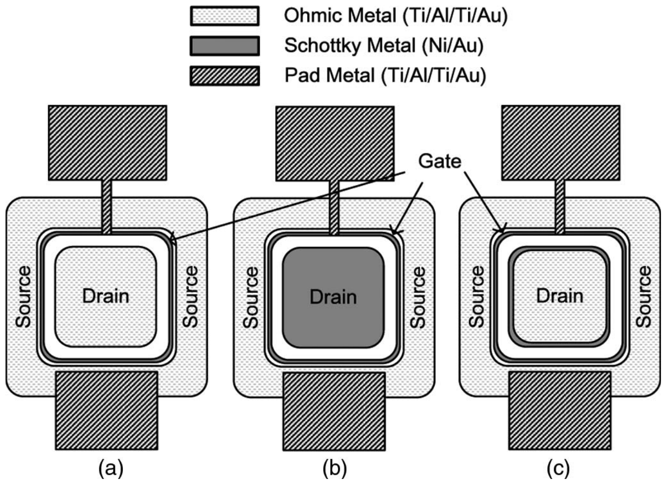

Fig. 2. Device layout of AlGaN/GaN HEMTs with different types of drain electrodes: (a) ohmic drain, (b) Schottky drain, and (c) hybrid drain.

GaN channel) and followed by a 24-nm UID $Al_{0.25}Ga_{0.75}N$ barrier layer. On the other hand, sample B consists of a 3.3-μm buffer layer, a 1.5-μm UID GaN layer, followed by a 20-nm $Al_{0.25}Ga_{0.75}N$ barrier layer and a 1-nm GaN cap layer. Although the exact structure of the buffer layer is not available, it usually requires an AlN layer on the Si substrate to prevent diffusion of Ga into Si. In addition, the AlN/GaN multistack layers or AlGaN layers are often used for growing a high-quality GaN channel. The mobility values, sheet resistances, and carrier concentrations of samples A and B are 1519 and 1492 $\mathrm{cm}^2/\mathrm{V} \cdot \mathrm{s}$, 476 and 432 $\Omega/\square$, and 8.6×10^{12} and $9.7 \times 10^{12}\ \mathrm{cm}^{-2}$, respectively.

The device active region was first isolated by inductively coupled plasma (ICP) dry etching using Cl_2/Ar mixture gas, and the etching depth is 300 nm. After defining the ohmic area by the photoresist, the samples were recessed by low-power Ar plasma treatment in an ICP system to reduce the ohmic contact resistance. The ohmic contacts were formed with Ti/Al/Ti/Au (20 nm/150 nm/45 nm/55 nm) by electron beam evaporation and then followed by rapid thermal annealing at 800 °C for 30 s in the nitrogen ambient. The metal stack of Ni/Au (20 nm/300 nm) was deposited to form the Schottky gate. Note that the Schottky gate metal (Ni/Au) was also utilized for the drain side Schottky metal of Schottky and hybrid drain devices. After finishing the Schottky metal deposition, a multilayer surface passivation composed of SiN and SiO was deposited by plasma-enhanced chemical vapor deposition. Note that the devices with ohmic, Schottky, and hybrid drain electrodes were simultaneously carried out on the same wafer and in close proximity to each other for a fair comparison.

Compared with the conventional ohmic drain device as shown in Fig. 1(a), the drain side Schottky metal of the proposed hybrid drain structure is deposited above the alloyed ohmic contact directly with an extension L_{ext} of 3 μm, as illustrated in Fig. 1(c). It should be emphasized that the gate–drain spacing L_{GD} of the hybrid drain devices is kept identical to the other two types of devices for a fair comparison of breakdown voltage. The extended Schottky metal has a smooth interface with the AlGaN layer (or GaN cap layer) and acts similar to a Γ-shaped field plate electrode, alleviating the electric field crowding effect in the vicinity of the drain ohmic contact. Fig. 2 depicts the device layout and metallization for the three types of devices. The square-gate layout is adopted to reduce the gate leakage current and mitigate the effects of traps originating from the dry etching damage at the sidewall of the mesa edge [12].

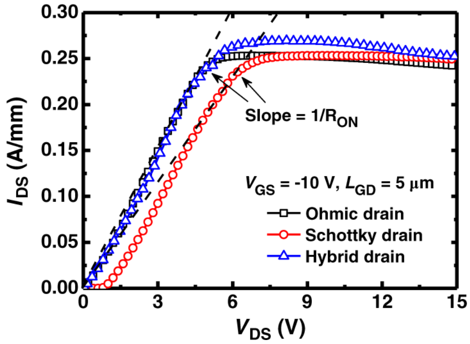

Fig. 3. $I_{DS}–V_{DS}$ characteristics of different structures in sample A.

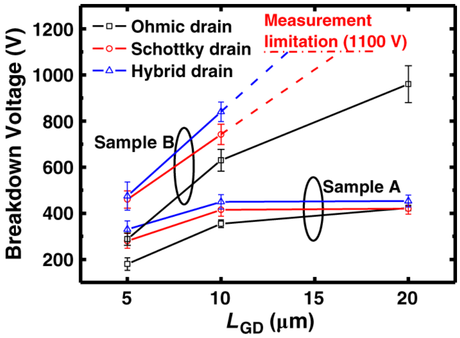

Fig. 4. Breakdown voltage V_{BK} as a function of the gate–drain spacing L_{GD} with three different structures at $V_{\mathrm{GS}} = -10$ V.

III. RESULTS AND DISCUSSION

The fabricated devices have the gate length (L_G) and gate–source spacing (L_{GS}) both of 2 μm, the gate width of 400 μm, and the gate–drain spacing (L_{GD}) varying from 5 to 20 μm. All the devices are the depletion mode with a similar V_{th} of ~ -2.9 V. Fig. 3 compares the $I_{DS}–V_{DS}$ characteristics of the three different structures realized in sample A (the results are averaged from three typical devices of each type). As shown, the proposed hybrid drain devices show a similar saturation current level with the other two types of devices. A similar trend is also observed for the devices in sample B. However, the Schottky drain devices exhibit a V_{on} of $\sim$1 V (the onset voltage of the Schottky contact), resulting in increased ON-resistance. With both the original ohmic and the extended Schottky current paths, there is no onset voltage observed for the proposed hybrid drain devices. Before V_{DS} exceeds V_{on} of the Schottky part of the drain contact, the current could still flow through the ohmic part of the contact. When the drain voltage becomes higher than the onset voltage, the drain Schottky electrode also turns on for current conduction. The calculated R_{on} in Fig. 3 is 1.80 $\mathrm{m}\Omega \cdot \mathrm{cm}^2$ for the hybrid drain devices, which is very close to that of 1.78 $\mathrm{m}\Omega \cdot \mathrm{cm}^2$ for the ohmic drain devices, whereas the Schottky drain devices show a much higher value of 2.33 $\mathrm{m}\Omega \cdot \mathrm{cm}^2$.

The breakdown voltage V_{BK} and OFF-state $I_{DS}–V_{DS}$ curves were measured under the three-terminal condition with a floated substrate by the Keithley high-voltage module with a limitation

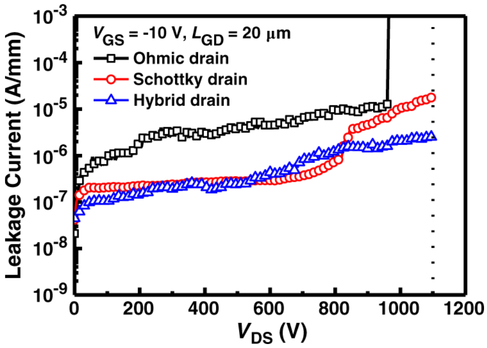

Fig. 5. OFF-state I_{DS}–V_{DS} characteristics of sample B.

of 1100 V. In addition, the samples were immersed into the Fluorinert FC-77 liquid to avoid surface flashover. The breakdown voltage is defined by the voltage corresponding to the drain current at 1 mA/mm. Fig. 4 shows the measured V_{BK} from both samples A and B (each data point is also the average of three typical devices with the error bars shown). Note that the V_{BK} of both the hybrid and Schottky drain devices in sample B with a L_{GD} of 20 μm exceed the measurement limitation as illustrated by the dashed lines using extrapolation. With a similar trend for both samples, it can be observed that the hybrid drain devices present, in general, the highest V_{BK}, and the conventional ohmic drain devices have relatively lower V_{BK}. The reason of V_{BK} enhancement for Schottky and hybrid drain devices could be attributed to the smooth interface between the Schottky metal and the AlGaN barrier layer (or GaN cap layer) and lack of metal spiking [8]. In addition, the hybrid drain devices present even higher V_{BK} than the pure Schottky drain structure. Compared with the pure Schottky drain devices, in which the peak electric field occurs at the edge of the drain Schottky metal, two electric field peaks exist in the hybrid devices at the vicinity of the drain contact. One peak locates at the edge of the ohmic portion, owing to metal spikes of the ohmic contact. The other peak occurs at the edge of the drain Schottky metal extension, which forms a Γ-shaped electrode and acts similar to a field plate to alleviate the high electric field around the metal spikes. This twin peak distribution can effectively alleviate and smooth out the electric field intensity around the drain side.

With a thinner buffer thickness, the breakdown voltages of the devices on sample A are lower than those observed in sample B. For sample A, V_{BK} obviously increases as L_{GD} increases from 5 to 10 μm but somehow saturated at $\sim$400 to 450 V when L_{GD} becomes 20 μm. The saturated V_{BK} is mainly due to the buffer leakage current in the vertical direction with a relatively thin buffer layer on the silicon substrate [5]. With a much thicker buffer layer of sample B, V_{BK} increases with L_{GD}, and the ohmic drain device with a L_{GD} of 20 μm can reach a breakdown voltage up to 960 V. Although not shown in Fig. 4, the devices with an even larger L_{GD} show increasing V_{BK} beyond 1100 V, which indicates that the sample B devices with a L_{GD} of 20 μm are still limited by the gate–drain breakdown rather than the Si substrate. The V_{BK} improvement of the Schottky and hybrid drain structures are 59.7% (170 V) and 64.9% (187 V) for devices with $L_{\mathrm{GD}} = 5$ μm and 17.5% (112 V) and 33.3% (210 V) for $L_{\mathrm{GD}} = 10$ μm, compared with the conventional ohmic drain devices.

Fig. 5 shows OFF-state I_{DS}–V_{DS} characteristics of the three types of devices in sample B with $L_{\mathrm{GD}} = 20$ μm. Both the Schottky and hybrid drain structures can suppress the leakage current by about one order of magnitude, compared with the conventional ohmic drain devices. Similarly, this can be attributed to the Schottky drain metal with a smooth contact interface, which can reduce the high electric field around the metal spikes and suppress the buffer leakage current.

IV. CONCLUSION

In this letter, we proposed a hybrid Schottky–ohmic drain structure for AlGaN/GaN HEMTs on a Si substrate, without the need of any additional photomasks and process steps. The Schottky metal extension formed a Γ-shaped electrode, reducing the peak electric field and smoothing the electric field distribution around the drain. The hybrid drain design also provided an extra current path to lower the ON-resistance. The measured results showed a zero onset voltage and reduced OFF-state leakage current by one order of magnitude compared with that of the traditional ohmic drain devices. The breakdown voltage was also significantly enhanced up to 64.9% without any degradation of the ON-resistance.

REFERENCES

[1] S. Arulkumaran, T. Egawa, S. Matsui, and H. Ishikawa, "Enhancement of breakdown voltage by AlN buffer layer thickness in AlGaN/GaN high-electron-mobility transistors on 4 in. diameter silicon," *Appl. Phys. Lett.*, vol. 86, no. 12, pp. 123 503–1–123 503–3, Mar. 2005.

[2] W. Saito, T. Noda, M. Kuraguchi, Y. Takada, K. Tsuda, Y. Saito, I. Omura, and M. Yamaguchi, "Effect of buffer layer structure on drain leakage current and current collapse phenomena in high-voltage GaN-HEMTs," *IEEE Trans. Electron Devices*, vol. 56, no. 7, pp. 1371–1376, Jul. 2009.

[3] S. L. Selvaraj, T. Suzue, and T. Egawa, "Breakdown enhancement of AlGaN/GaN HEMTs on 4-in silicon by improving the GaN quality on thick buffer layers," *IEEE Electron Device Lett.*, vol. 30, no. 6, pp. 587–589, Jun. 2009.

[4] Y. C. Choi, M. Pophristic, H. Y. Cha, B. Peres, M. G. Spencer, and L. F. Eastman, "The effect of an Fe-doped GaN buffer on OFF-state breakdown characteristics in AlGaN/GaN HEMTs on Si substrate," *IEEE Electron Device Lett.*, vol. 53, no. 12, pp. 2926–2928, Dec. 2006.

[5] N. Ikeda, S. Kaya, J. Li, T. Kokawa, M. Masuda, and S. Katoh, "High-power AlGaN/GaN MIS-HFETs with field-plates on Si substrates," in *Proc. 21st Int. Symp. Power Semicond. Devices IC's*, Jun. 2009, pp. 251–254.

[6] I. B. Rowena, S. L. Selvaraj, and T. Egawa, "Buffer thickness contribution to suppress vertical leakage current with high breakdown field (2.3 MV/cm) for GaN on Si," *IEEE Electron Device Lett.*, vol. 32, no. 11, pp. 1534–1536, Nov. 2011.

[7] P. Srivastava, J. Das, D. Visalli, M. V. Hove, P. E. Malinowski, D. Marcon, S. Lenci, K. Geens, K. Cheng, M. Leys, S. Decoutere, R. P. Mertens, and G. Borghs, "Record breakdown voltage (2200 V) of GaN DHFETs on Si with 2-μm buffer thickness by local substrate removal," *IEEE Electron Device Lett.*, vol. 32, no. 1, pp. 30–32, Jan. 2011.

[8] B. Lu, E. L. Piner, and T. Palacios, "Schottky-drain technology for AlGaN/GaN high-electron mobility transistors," *IEEE Electron Device Lett.*, vol. 31, no. 4, pp. 302–304, Apr. 2010.

[9] Y. Dora, A. Chakraborty, S. Heikman, L. McCarthy, S. Keller, S. P. DenBaars, and U. K. Mishra, "Effect of ohmic contacts on buffer leakage of GaN transistors," *IEEE Electron Device Lett.*, vol. 27, no. 7, pp. 529–531, Jul. 2006.

[10] E. Bahat-Treidel, R. Lossy, J. Würfl, and G. Tränkle, "AlGaN/GaN HEMT with integrated recessed Schottky-drain protection diode," *IEEE Electron Device Lett.*, vol. 30, no. 9, pp. 901–903, Sep. 2009.

[11] C. Zhou, W. Chen, E. L. Piner, and K. J. Chen, "Schottky-ohmic drain AlGaN/GaN normally off HEMT with reverse drain blocking capability," *IEEE Electron Device Lett.*, vol. 31, no. 7, pp. 668–670, Jul. 2010.

[12] Y. S. Lin, J. Y. Wu, C. Y. Chan, S. Hsu, C. F. Huang, and T. C. Lee, "Square-gate AlGaN/GaN HEMTs with improved trap-related characteristics," *IEEE Trans. Electron Devices*, vol. 56, no. 12, pp. 3207–3211, Dec. 2009.