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High-breakdown-voltage (>3000 V) and low-power-dissipation $Al_{0.3}Ga_{0.7}N/GaN/Al_{0.1}Ga_{0.9}N$ double-heterostructure HEMTs with Ohmic/Schottky hybrid drains and Al_2O_3/SiO_2 passivation

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GaN power devices have broad application prospects in fast charging systems, power supplies, data centers, and electric vehicles due to their high critical breakdown field strength, high switching frequency, and high conversion efficiency [1–3]. AlGaN/GaN/AlGaN double-heterostructure (DH) high-electron-mobility transistors (HEMTs) have been extensively studied owing to their low leakage current and low off-state power dissipation. Although investigations on DH-HEMTs have achieved great breakthroughs regarding the static power dissipation in recent years, the dynamic characteristics and reliability of DH-HEMTs have rarely been studied. Moreover, DH-HEMTs are required to further improve the breakdown voltage and reduce the power dissipation of devices to meet the requirements of numerous applications, such as electric vehicles/hybrid electric vehicles and the charging infrastructure. In this study, $Al_{0.3}Ga_{0.7}N/GaN/Al_{0.1}Ga_{0.9}N$ DH-HEMTs with an Ohmic/Schokkty hybrid drain and Al_2O_3/SiO_2 passivation were fabricated. A high breakdown voltage of more than 3000 V and a leakage current below 0.1 μA/mm were achieved for the $Al_{0.3}Ga_{0.7}N/GaN/Al_{0.1}Ga_{0.9}N$ DH-HEMTs. Moreover, these devices exhibit excellent dynamic characteristics.

Material growth and device fabrication. The $Al_{0.3}Ga_{0.7}N$ (24 nm)/GaN (10 nm)/$Al_{0.1}Ga_{0.9}N$ (200 nm) epitaxial wafer used in this study was grown onto a two-inch C-plane sapphire substrate via metal-organic chemical vapor deposition (MOCVD). The first step of the device fabrication consisted of isolating the mesa. Subsequently, two types of DH-HEMTs with different drain contacts (i.e., a conventional Ohmic drain and an Ohmic/Schottky hybrid drain) were fabricated on the same wafer. The gate metal and the Schottky contact in the drain were fabricated through a one-step lithography process and electron beam evaporation. Then, 3 nm Al_2O_3 and 800 nm SiO_2 were sequentially deposited using thermal atom layer deposition (ALD) and plasma-enhanced chemical vapor deposition (PECVD), respectively, for passivating the DH-HEMTs. Finally, contact vias were opened via ion-beam etching, and the power metal Ni/Au (50/500 nm) used for interconnection was deposited using electron beam evaporation. Figure 1(a) shows the cross-sectional schematic profiles of the DH-HEMTs with an Ohmic/Schottky hybrid drain.

Results and discussion. Figure 1(b) shows the output characteristics of the DH-HEMTs with an Ohmic/Schottky hybrid drain and conventional Ohmic drain. Figure 1(c) shows the transfer and gate leakage characteristics of the DH-HEMTs with the different drain structures. Both devices present similar transfer and gate leakage curves. Figure 1(d) shows the I_{ON}/I_{OFF} ratio and SS as a function of temperature. The I_{ON}/I_{OFF} ratio remains as high as 10^9 for the DH-HEMTs with a hybrid drain at 473 K. SS increases from 63 to 105 mV/dec as the measurement temperature increased from room temperature to 473 K. These results indicate that the DH-HEMTs with a hybrid drain have excellent high temperature characteristics. The threshold voltage shift (V_{TH}) as a function of the duration of the applied stress under different gate bias stresses is illustrated in Figure 1(e). The V_{TH} shift is less than 0.25 V under gate bias stresses of −20, −10, and 2 V. Figure 1(f) shows the off-state breakdown characteristics of the DH-HEMTs with a hybrid drain and different L_{GD} values. The breakdown

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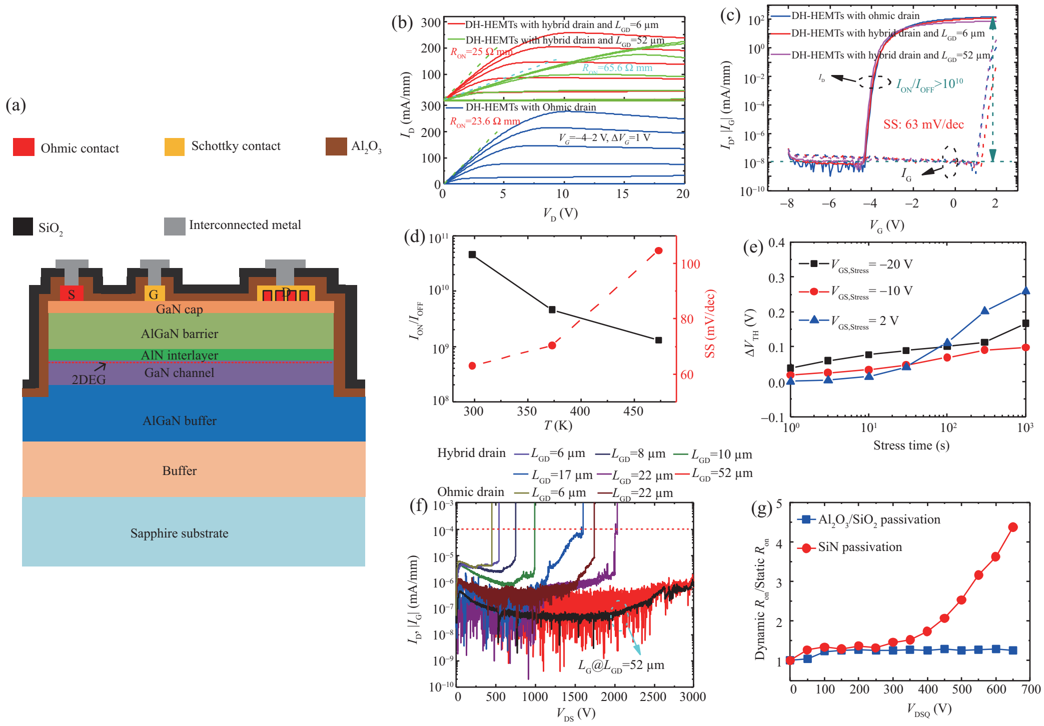

Figure 1 (Color online) (a) Cross-sectional schematic profiles of the DH-HEMTs with an Ohmic/Schottky hybrid drain. (b) Output characteristics and (c) transfer characteristics of the $Al_{0.3}Ga_{0.7}N/GaN/Al_{0.1}Ga_{0.9}N$ DH-HEMTs with different drain structures and L_{GD} = 6, 52 μm. (d) I_{ON}/I_{OFF} ratio and SS as a function of temperature. (e) V_{TH} as a function of the duration of the applied stress under different gate bias stresses. (f) Breakdown characteristics of the $Al_{0.3}Ga_{0.7}N/GaN/Al_{0.1}Ga_{0.9}N$ DH-HEMTs with a hybrid drain and a conventional Ohmic drain at $V_{GS} = -8$ V. The gate leakage current curve for L_{GD} = 52 μm is also illustrated. (g) Normalized R_{on} at different quiescent drain bias points.

voltage (V_{BR}) is defined as the drain voltage at which the leakage current reaches 0.1 μA/mm. The V_{BR} values of the DH-HEMTs with a hybrid drain are 553, 747, 990, 1598, and 2032 V for L_{GD} = 6, 8, 10, 17, and 22 μm, respectively. The V_{BR} of the DH-HEMTs with a hybrid drain is greater than that with a conventional Ohmic drain owing to the better edge and surface metal morphology [4]. It is worth noting that, in the case of L_{GD} = 52 μm, the breakdown voltage exceeds 3000 V. Additionally, the off-state leakage current at V_{DS} = 3000 V is around 10^{-6} mA/mm, which indicates that the off-state power dissipation is only 3 μW/mm. Figure 1(g) shows the dynamic on-resistance (R_{on}) degradation of the DH-HEMTs with a hybrid drain and Al_2O_3/SiO_2 passivation and the DH-HEMTs with a hybrid drain and SiN passivation at different quiescent drain bias points. The dynamic R_{on} of the devices was measured under soft switching using the pulse *I*-*V* system. The pulse period is 50 ms. The pulse width of the drain and gate bias is 500 and 300 μs, respectively. The delay time between the drain and gate pulses is 100 μs. The dynamic R_{on} dispersion is less than 30% under a quiescent drain bias of up to 650 V of the DH-HEMTs with a hybrid drain and Al_2O_3/SiO_2 passivation which is less than that of the DH-HEMTs with a hybrid drain and SiN passivation. The devices passivated by PECVD-SiN have a high interface state density, resulting in a serious dynamic R_{on} degradation [5]. Al_2O_3 deposited by ALD has a better interface quality and a reduced interface state density, which can suppress dynamic R_{on} degradation. Moreover, Al_2O_3 can protect the AlGaN surface from plasma damage during the PECVD-SiN process. Therefore, the devices with Al_2O_3/SiO_2 passivation showed excellent dynamic characteristics.

Conclusion. A novel $Al_{0.3}Ga_{0.7}N/GaN/Al_{0.1}Ga_{0.9}N$ DH-HEMT with an Ohmic/Schottky hybrid drain and Al_2O_3/SiO_2 passivation was proposed. A high V_{BR} of more than 3000 V and an extremely low power dissipation were achieved. The dynamic R_{on} dispersion was well suppressed owing to the Al_2O_3/SiO_2 passivation. These results indicate that the fabricated DH-HEMTs have significant potential for high-temperature and high-power applications.

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