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2.29-kV GaN-based double-channel Schottky barrier diodes on Si substrates with high VON uniformity

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The GaN on Si technology is attractive for power electronic systems owing to its low cost and large wafer size [1]. GaN Schottky barrier diodes (SBDs) on Si substrates have been extensively studied due to their superior power figure of merit and fast reverse recovery features [2]. Despite substantial advances in GaN SBDs research in recent years, the device performance remains below the theoretical predictions. GaN SBDs are needed to enhance the turn-on voltage, specific on-resistance, and breakdown voltage for power electronic applications. An anode-recessed structure was adopted in AlGaN/GaN SBDs to reduce the turn-on voltage (VON) [3]. However, it is difficult to fabricate anode-recessed SBDs with a uniform VON on a large sized wafer. Furthermore, thermal stability is also necessary for space applications like aerospace exploration.

Novel $\mathrm{Al_{0.4}Ga_{0.6}N}$/(AlN/GaN super-lattices)/AlN/$\mathrm{Al_{0.1}Ga_{0.9}N}$ double-channel (DC) SBDs with an anode-recessed structure on a 6-inch Si substrate are proposed in this study to enhance the VON uniformity and thermal stability of GaN SBDs. A smooth etching profile was achieved through a two-step inductive coupled plasma (ICP) etching process. The anode-recessed DC-SBDs achieved a low VON of 0.5 V with a tight distribution of 0.007 V. The thermal stability of the devices was improved through enhanced two-dimensional electron-gas (2DEG) confinement for the upper channel and weak mobility degeneration for the lower channel. Moreover, the anode-recessed DC-SBDs with an anode-to-cathode distance of 30 m achieved a high breakdown voltage of 2290 V.

Material growth and device fabrication. The epilayer employed in this study was grown using metal-organic chemical vapor deposition on a 6-inch p-type Si (111) substrate. From bottom to top, the epitaxial structure consists of a 200 nm AlN nucleation layer, two $\mathrm{Al_{0.75}Ga_{0.25}N}$ (500 nm)/$\mathrm{Al_{0.5}Ga_{0.5}N}$ (500 nm) intermediate layers, a 2.5 micron $\mathrm{Al_{0.1}Ga_{0.9}N}$ layer, a 2 nm AlN layer, a 120 nm AlN(1 nm)/GaN(5 nm) super-lattices (SLs) layer, a 25 nm $\mathrm{Al_{0.4}Ga_{0.6}N}$ barrier layer, and a 2 nm GaN cap layer. The intermediate layers $\mathrm{Al_{0.75}Ga_{0.25}N}$/$\mathrm{Al_{0.5}Ga_{0.5}N}$ were introduced for stress management to grow the thick $\mathrm{Al_{0.1}Ga_{0.9}N}$ buffer layer for high-voltage applications. The 2 nm AlN layer was designed as a back-barrier for the upper 2DEG channel and barrier for the lower 2DEG channel. GaN/AlN SLs were used as the 2DEG channel layer because of their enhanced breakdown field strength and reduced alloy disorder scattering [4]. Figure 1(a) displays the cross-sectional scheme of the epitaxial structure. The van der Pauw Hall measurements show an electron sheet density of 6.12×10^{12} $\mathrm{cm^{-2}}$ and an electron mobility of 433 $\mathrm{cm^2{\cdot}V^{-1}{\cdot}s^{-1}}$.

The device fabrication procedure began with mesa isolation using ICP etching. Subsequently, the cathode ohmic metals Ti/Al/Ni/Au (20 nm/140 nm/45 nm/55 nm) were deposited by electron beam (EB) evaporation, followed by annealing for 45 s in N_2 ambient conditions. The transfer length method was adopted to calculate the ohmic contact resistance (1.2 Ω·mm). An anode-recessed structure was constructed by the two-step ICP etching processes. First, after the definition of the anode recess regions, the AlGaN barrier layer was etched away using a $\mathrm{Cl_2/BCl_3}$-based ICP with a flow rate of 10/25 sccm. To minimize plasma-induced damage, a low etching rate of 1.6 $\mathrm{nm{\cdot}min^{-1}}$ could be attained. Next, a Ni/Au (45 nm/200 nm) bilayer was evaporated to fabricate the anode electrode, with the anode overlapping the GaN cap by 2 μm. Finally, 20 nm of $\mathrm{Al_2O_3}$ was deposited using thermal atomic layer deposition to passivate the device. The anode-to-cathode distance (LAC) varies from 5 to 30 μm. Figure 1(a) shows a cross-sectional view of the DC-SBDs with the anode-recessed structure. SBDs without the anode-recessed structure were also manufactured on the same wafer for comparison.

Results and discussion. The temperature-dependent for-

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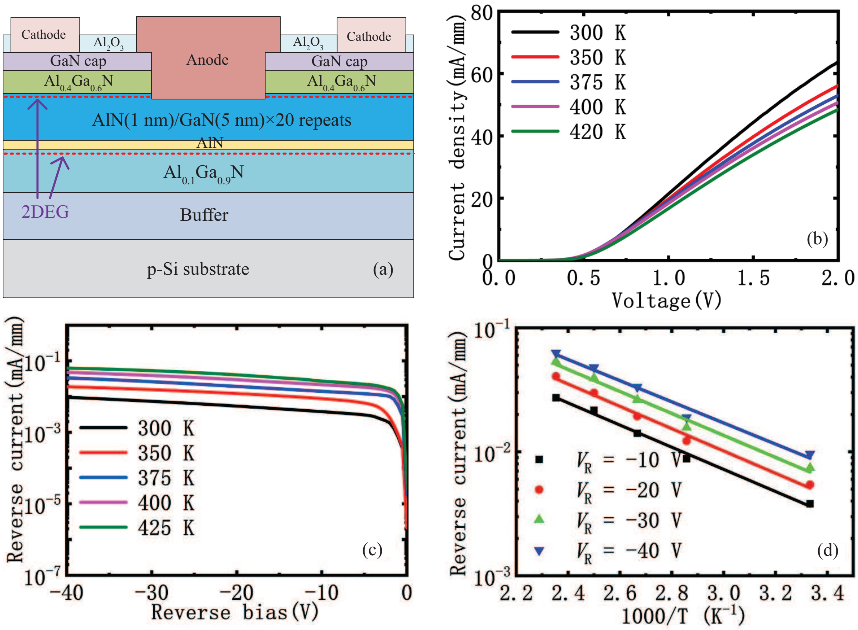

Figure 1 (Color online) (a) Cross-sectional schematics of the DC-SBDs with the anode-recessed structure; (b) forward I-V and (c) reverse I-V characteristics of recessed DC-SBDs at elevated temperatures; (d) Arrhenius plot of the reverse current at $V_R = -10, -20, -30$, and -40 V as a function of the reciprocal temperature.

ward I-V characteristics of the recessed DC-SBDs are shown in Figure 1(b). The forward current of the recessed DC-SBDs at 2 V was observed to decrease with increasing the measurement temperature. The forward current for AlGaN/GaN SBDs at 425 K usually drops below 0.60 of the room temperature value [4]. Conversely, the forward current (at 2 V) for the recessed DC-SBDs at 425 K reached 0.75 of the room temperature value. This is attributed to the fact that the large conduction band discontinuity at the GaN/AlN heterointerface can promote the confinement of the upper 2DEG. Additionally, the mobility of 2DEG in the lower AlGaN channel heterostructure drops less at higher temperatures than in the AlGaN/GaN heterostructure [5].

Figure 1(c) displays the temperature-dependent reverse I-V characteristics of the recessed DC-SBDs. Below the pinch-off voltage ($V_R < -2.5$ V), the reverse current is insensitive to the reverse bias but increases with increasing temperature. As a result, the Fowler-Nordheim tunneling and variable-range-hopping mechanisms are both ruled out. The reverse current at $V_R = -10, -20, -30$, and -40 V exhibits a linear behavior as a function of the reciprocal temperature, as illustrated in Figure 1(d), suggesting an Arrhenius-type thermally activated mechanism. The trap-assisted tunneling (TAT) is the most likely carrier transport mechanism below the pinch-off voltage [3,6]. The activation energy can be extracted from the linear fit to the data in Figure 1(d). At $V_R = -10, -20, -30$, and -40 V, the corresponding values of E_A were found to be 0.177, 0.179, 0.176, and 0.169 eV for the recessed DC-SBDs. These extracted E_A are similar to the values of 0.16 and 0.18 eV reported in [6,7], respectively. Liang et al. [6] discovered that N_2 plasma treatment results in higher E_A and a reduced reverse leakage. The N_2 plasma treatment in the recessed region will be implemented to reduce the reverse leakage in our next study.

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