The unique material properties of Gallium Nitride (GaN) enable excellent figure-of-merit for power electronic devices have been of great interest to researchers and engineers for the past two decades. In the case of lateral devices, the most distinctive feature of GaN-based materials is the high 2-dimensional electron gas (2DEG) density (e.g. $\sim 1 \times 10^{13}$ cm$^{-2}$) generated at the interface of AlGaN/GaN heterojunction, which features exceptional electron mobility as high as $\sim 2000$ cm$^2$/V·s at room temperature$^1$ due to its strong piezoelectric and spontaneous polarization effect.$^2$ Therefore, with the help of the wide bandgap property, the electronic devices based on AlGaN/GaN heterojunction are capable of achieving high switching speed, low switching loss, low conduction loss, high breakdown voltage and high temperature operation, which are highly preferred for power electronic applications.$^3$ For power electronics the AlGaN/GaN on Si substrate has been considered as a promising technology for next generation power devices with low-cost and high performance due to the large diameter wafer up to 8-inch$^4$ and the well developed CMOS compatible process. As a result, the mass fabrication of AlGaN/GaN power devices with the mainstream CMOS fabrication lines becomes feasible.$^5$ Besides featuring the superior power performance, AlGaN/GaN-on-Si power devices can further be monolithically integrated with conventional Si CMOS circuits suggesting the possibility of realizing single-chip compact GaN power integrated circuits (ICs).$^3$ For power applications, most of the aforementioned efforts have been focused on the three-terminal AlGaN/GaN transistors to achieve enhancement-mode (E-mode) operation.$^6$−$^9$ Lower leakage current yet high breakdown voltage, $I_{\text{leakage}}$ and low current collapse.$^{10}$−$^{12}$ On the other hand, the two terminal power diode as an indispensable component for switching power converters also attracts broad attention recently.$^{23}$−$^{25}$

In this work, a novel AlGaN/GaN MIS-Gated Hybrid Anode Diode (MG-HAD) that allows flexible control of the forward turn-on voltage ($V_T$) is demonstrated by simply varying the recess depth at the MIS-Gated region. It features a new turn-on and current conduction mechanism. The diode features ultralow diode turn-on voltage, $V_T$, low conduction loss, low radio frequency leakage, and low reverse leakage. Besides the superior device performance, the MG-HAD is fully compatible with the E-mode trench gate AlGaN/GaN MISFET, which allows monolithic integration of E-mode AlGaN/GaN transistors with the MG-HAD for single-chip AlGaN/GaN-on-Si smart power ICs.

### Device Structure and Operation Mechanism

The schematic device structure of the proposed MG-HAD is shown in Fig. 1. The anode features a recessed MIS-Gate-controlled 2DEG channel that is electrically connected with an ohmic contact. The turn-on voltage ($V_T$) is determined by the threshold voltage of MIS-Gated channel instead of the conventional Schottky barrier height. Thus the $V_T$ can be freely tailored by adjusting the recess depth of the MIS-Gate. Moreover, as shown in Fig. 2a, the on-state current in forward bias is conducted between the two ohmic contacts at the anode and cathode, which leads to inherent lower $R_{\text{on}}$ of the MG-HAD than that in the conventional Schottky-barrier-diode (SBD) with a Schottky contact at the anode. In reverse bias the 2DEG channel beneath the MIS-Gate is fully depleted for reverse blocking as shown in Fig. 2b. Hence, the current control and conduction are fundamentally separated in the MG-HAD.

It can be inferred that in order to experimentally obtain a respectful low $V_T$, the device fabrication process requires delicately design for the depth of the gate trench. Hence, the device simulation was carried out by TCAD Sentaurus to optimize the gate trench for tailoring forward turn-on voltage $V_T$. The AlGaN/GaN heterostructure in the simulation consists of 2 nm GaN-cap, 23 nm Al$_0.23$Ga$_{0.77}$N barrier, 3.5 $\mu$m GaN buffer. A 20 nm Al$_2$O$_3$ thin film was used as the gate dielectric which is identical to that used in device fabrication. The simulated forward current-voltage characteristics of the MG-HAD and the extracted $V_T$ varies with the gate trench depth are depicted in Figs. 3a and 3b, respectively. It can be seen that the trench depth...
Figure 2. (a) The current conduction mechanism of the MG-HAD in forward bias and (b) the reverse blocking mechanism of the MG-HAD in reverse bias.

Figure 3. (a) The simulated forward characteristics of the MG-HAD, and (b) the extracted forward turn-on voltage $V_T$ (at 1 mA/mm) with different recessed-barrier-thickness (Inset: The I-V curves of the MG-HAD in semi-log scale).

effectively affects the forward turn-on characteristics of the MG-HAD. The drive current density shows a slight decrease with thinner recessed-barrier-thickness $T$ due to the enhanced depletion effect of the 2DEG and subsequently larger channel resistance beneath the trench gate. On the contrary, the $V_T$ (defined at 1 mA/mm) decreases from 0.9 to 0.27 V while the recessed-barrier-thickness $T$ increases from 1 to 5 nm. This is the result of the diminishing depletion effect on 2DEG with thicker AlGaN barrier. Since the lower $V_T$ is favored for lowering the forward conduction power loss of the diode, $T = 3–5$ nm with the corresponding $V_T$ in the range of 0.27–0.42 V was selected as the optimal trench depth in device fabrication.

Fig. 4a shows the conduction band minimum ($E_C$) diagram versus the lateral position extracted at the hetero-interface of the MG-HAD with recessed-barrier-thickness $T = 2$ nm at different bias voltage $V_{AC}$ ($-2$, $0$, $+2$, $+4$ and $+6$ V). The bias voltage applied at the anode is capable of sufficiently modulating the conduction band and then the energy barrier presented at the gate region. At $V_{AC} = 0$ V, an energy barrier of $\sim 1$ eV is formed at the gate region due to the intrinsic depletion effect originates from the barrier recess while the native normally-on channel is turned into a normally-off channel. Accordingly, the 2DEG density reduced from $1.7 \times 10^{19}$ cm$^{-3}$ to $1.26 \times 10^{14}$ cm$^{-3}$ at the gate region as shown in Fig. 4b. In forward bias (e.g. $V_{AC} > 0$ V), the energy barrier is eliminated with 2DEG populated beneath the gate (see Fig. 4b), forming a high conductive path between the two ohmic contacts at the anode and cathode, effectively turn on the MG-HAD. In reverse bias, on the other hand, the energy barrier is raised up to further block the current flow from anode to cathode, with strong depletion effect as shown in Fig. 4b. The valley observed in the 2DEG density at the cathode-side gate edge is induced by the localized-peak electric-field in reverse bias. The insertion of high-$k$ gate dielectric is beneficial for suppressing the reverse leakage current through the trench gate and simultaneously maintaining excellent channel modulation capability of the Gate.

Device Fabrication and Measurement Results

The proposed AlGaN/GaN heterostructure used in experiments consists of 2 nm GaN-cap and a 23 nm Al$_{0.23}$Ga$_{0.77}$N barrier that is identical to the simulation model. At the AlGaN/GaN hetero-interface, 1 nm AlN spacer was inserted to improve the hetero-interface quality as well as the 2DEG mobility. The buffer layer consists of AlN initial nucleation layer, a super lattice layer followed by GaN, 200 nm Al$_{0.05}$Ga$_{0.95}$N back barrier and 50 nm GaN channel layer. Compared with the conventional GaN buffer, the Al$_{0.05}$Ga$_{0.95}$N back barrier is able to effectively suppress the buffer leakage, which is intentionally used
to further reduce the reverse leakage current of the fabricated device.\textsuperscript{16} The device fabrication process is identical to our previous work.\textsuperscript{26} The SiNx passivation layer of 100 nm was deposited by PECVD prior to the 20 nm ALD-Al$_2$O$_3$ gate dielectric. The hybrid gate recess technology\textsuperscript{13} was performed to precisely control the recess depth. The recessed-barrier-thickness $T$ was then confirmed to be 4 nm by AFM that is well reconcile with the optimal trench depth obtained by simulation. For comparison, the conventional SBD with Schottky metal stack directly deposited on III-Nitride semiconductor as the anode was also fabricated on the epi structure without the back barrier. The metal stack used for the ohmic contacts was Ti/Al/Ni/Au, while the Ni/Au metal stack was used as the Schottky metal for the Gate in the MG-HAD and Schottky anode in the SBD. The measured forward $I$-$V$ curves of the MG-HAD and the conventional SBD with anode-to-cathode spacing ($L_{AC}$) of 5 $\mu$m are plotted in Fig. 5a. The forward turn-on voltage $V_T$ exhibits a significant reduction in the MG-HAD. Moreover, the MG-HAD delivers a substantial higher current density at comparable voltage than the conventional SBD. It also validates the novel conduction mechanism of the proposed MG-HAD, and the achieved superior intrinsic device performance. Fig. 5b shows the forward characteristics of the MG-HAD with different $L_{AC}$. It can be seen that the devices exhibit stable turn on characteristics and the turn on voltage is consistently less than 1 V. Fig. 6 shows the statistical plot of $V_T$ for 39 diodes with different $L_{AC}$ fabricated on a 2 $\times$ 2 cm$^2$ sample. The $V_T$ exhibit a small deviation exemplifies that the turn on mechanism governed by the MIS-Gated channel can be well controlled and reveals that large periphery device with ultra-low $V_T$ also can be fabricated. In the fabricated device, the $V_T$ as low as 0.2 V is obtained that is the minimum forward turn-on voltage of GaN-based diode up to date. It should be noted that it is still possible to further reduce the $V_T$ by slightly reducing the trench depth.

The reverse characteristics of the MG-HAD and the conventional SBD with $L_{AC}$ of 5 $\mu$m are compared in Fig. 7. At comparable voltage the reverse leakage current is significantly reduced by 3 orders of magnitude in the MG-HAD. The breakdown voltage for the SBD and MG-HAD is defined at reverse leakage current of 1 mA/mm and 1 $\mu$A/mm, respectively. Even with a more rigorous criterion, the $BV$ is still improved from 224 to 412 V. Fig. 8 shows the $BV$ of the MG-HADs with different $L_{AC}$ and compared with that measured in the conventional SBDs. It can be seen that the MG-HADs exhibit a consistently respectable enhancement in $BV$ even with much lower leakage current. Such a significant improvement in reverse leakage and then the breakdown voltage of the MG-HAD is dominated by the novel device structure of MIS-Gate controlled channel. Owing to the employment of AlGaN back barrier, the MG-HADs reported in this work achieve further reduced leakage current by one order of magnitude than our previous work.\textsuperscript{26} The highest $BV$ of more than 1.1 kV is obtained in a MG-HAD with $L_{AC}$ of 20 $\mu$m at leakage current less than 1 $\mu$A/mm. The proposed MG-HADs exhibit competitive performance and better trade off between the ultralow $V_T$ and high $BV$.
Conclusions

A novel AlGaN/GaN lateral diode featuring a MIS-Gated hybrid anode was demonstrated in this paper. The operation mechanism of the device was studied in detail and device performance was also optimized by simulation. Benefiting from the turn-on control mechanism determined by the threshold voltage of the MIS-Gated 2DEG channel instead of the built-in potential in Schottky junction, the MG-HAD exhibits ultralow turn-on voltage and reverse leakage current. This is instead of the built-in potential in Schottky junction, the MG-HAD is fully compatible with the trench gate E-mode AlGaN/GaN MISFETs which paves the way for single-chip integration of GaN transistors and diodes.

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