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PAPER

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Thin-barrier gated-edge termination AlGaN/GaN Schottky barrier diode with low reverse leakage and high turn-on uniformity

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Abstract

In this study, novel AlGaN/GaN Schottky barrier diodes (SBDs) are fabricated with thin-barrier (5 nm) AlGaN/GaN heterostructures, featuring recess-free technology, eliminating bombardment plasma damage, and leading to high device uniformity. Combining a gated-edge termination (GET) design and assistance with high-quality low-pressure chemical vapor deposition SiN_x, a low reverse leakage current ($\sim$10 nA mm^{-1} @ -600 V) and a high reverse breakdown voltage of over 1.78 kV (@1 μA mm^{-1}) are obtained. At the same time, we achieve a low turn-on voltage of 0.57 V and a low differential on-state resistance $R_{on,sp}$ of 1.49 mΩ cm^2 for thin-barrier GET SBDs with an anode-to-cathode distance (L_{AC}) of 15 μm, yielding a Baliga's figure of merit of 2120 MW cm^{-2}. Moreover, this proposed diode process flow is compatible with AlGaN/GaN high-electron-mobility transistors, which is promising for its integration in the smart GaN platform.

Keywords: AlGaN/GaN, Schottky barrier diode, lateral, high breakdown voltage, low turn-on voltage, gate-edge termination

(Some figures may appear in colour only in the online journal)

1. Introduction

AlGaN/GaN-based heterojunction Schottky barrier diodes (SBDs) are promising for next-generation electrical power systems due to their superior material properties, such as high mobility, high electric breakdown strength and high-electron saturation velocity [1, 2]. In particular, two-dimensional electron gas (2DEG) with high mobility and sheet charge density at the AlGaN/GaN interface gives rise to more efficient SBDs compared with conventional silicon power devices. In addition, AlGaN/GaN-based SBDs are compatible with the process flow of AlGaN/GaN high-electron-mobility transistors (HEMTs), which is promising for GaN power integrated circuits [3].

For a high-efficiency power system, a low turn-on voltage, a high breakdown voltage and a low reverse leakage are preferred. Various SBD designs and processing techniques have been discussed for the optimization of AlGaN/GaN SBDs, including partially recessed SBDs [4, 5], over-etched with sidewall contacted SBDs [6], hybrids [7–10], and 3D tri-anode SBDs [11, 12]. However, the reverse leakage of SBDs is still

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relatively high (above 10^{-4} mA mm^{-1}). A few termination techniques have been proposed to suppress the leakage current by reducing the electric field at the Schottky edge, such as the p-GaN field plate [13] and gated-edge termination (GET) [5]. GET is preferred for its simplicity to fabricate, since it does not require a large area of etching in the access region, unlike the p-GaN field plate. Meanwhile, the electric field in the vicinity of the Schottky edge can be effectively reduced by depletion of the 2DEG channel under the metal–insulator–semiconductor (MIS) field plate at low reverse bias, resulting in low leakage when the reverse voltage increases. Two approaches have been proposed to enhance the modulation capability of the MIS field plate to the 2DEG channel beneath, including a partially recessed barrier [5, 14] and a 3D tri-anode [15]. However, the etch damage to the AlGaN barrier in the Schottky region or field plate region for these two approaches might bring about potential reliability issues [16].

Therefore, in this work, a recess-free thin-barrier GET AlGaN/GaN SBD (TB-GET) with Ni/Au Schottky metal has been proposed to address the above challenge, aiming to reduce the plasma damage both in the Schottky region and under the MIS field plate. Benefiting from the as-grown thin-barrier epistructure, it allows us to obtain a low turn-on voltage without recess of the barrier, as well as to perform GET termination without recess of the barrier to lower the reverse leakage without affecting the forward characteristics.

2. Device structure

The AlGaN/GaN heterostructure epitaxial wafer starts from a low resistive 4 inch Si <111> substrate, followed with a ~4 μm C-doped GaN buffer stack, a 200 nm GaN channel, a 1 nm AlN interface enhancement layer and a 5 nm $Al_{0.25}Ga_{0.75}N$ barrier (dislocation density is ~1E9 cm^{-2}).

A schematic cross-section of the recess-free TB-GET with two different thicknesses of low-pressure chemical vapor deposition (LPCVD) SiN_x is shown in figure 1. The purpose of fabricating these two different SiN_x thicknesses is to investigate the impact of SiN_x thickness on reverse leakage. The fabrication flow starts with the deposition of an LPCVD SiN_x passivation layer to restore the 2DEG for the as-grown thin-barrier AlGaN/GaN heterostructure [17]. With both 24 nm and 10 nm LPCVD SiN_x passivation, the sheet resistance can be reduced from 1780 Ω sq^{-1} to 450 Ω sq^{-1}. Meanwhile, the LPCVD SiN_x plays an important role as part of the GET field plate to suppress leakage current as well. Then, the cathode electrode (C) of the SBD is made of Ti/Al/Ni/Au after LPCVD SiN_x removal in the cathode region and annealed at 850 °C for 50 s. The ohmic contact resistance (R_c) was measured and calculated as 0.65 Ω mm using the transfer length method. After device isolation formed by N implantation, the anode electrode (A) is formed by opening the LPCVD SiN_x passivation with fluorine-based inductively-coupled-plasma (ICP) etching and cleaning, followed by Ni/Au Schottky metal evaporation. Finally, the devices are passivated with 200 nm SiN_x by plasma-enhanced CVD.

On-wafer DC characterization is carried out on single-finger diodes with an anode finger width (W) of 100 μm, an anode-to-cathode length (L_{AC}) of 6 μm and a Schottky junction length (L_{SC}) of 6 μm for TB-GET with 24 nm and 10 nm LPCVD SiN_x. The measured current–voltage (I–V) characteristics of small diodes, as a function of the anode-to-cathode voltage V_{AC}, is shown in figure 2. The forward I–V characteristics are shown in figure 2(a), where both of the samples show similar forward characteristics, because the turn-on voltage (V_T) is determined by the thickness of the as-grown AlGaN barrier layer [4] and the forward current is determined mostly by the 2DEG sheet resistance and R_c, regardless of the LPCVD SiN_x thickness [17]. The TB-GET with 24 nm SiN_x shows high reverse leakage, while the reverse leakage current of TB-GET with 10 nm SiN_x is one order of magnitude lower (figure 2(b)). This leakage reduction is ascribed to the electric field at the Schottky barrier corner being drastically reduced and the peak being shifted to the GET corner, leading to a reduction of reverse leakage, which was revealed by the simulated electric field distribution shown in the figures 2(c)–(e).

Typical forward and reverse leakage and breakdown characteristics of recess-free TB-GET (100 μm width) with varying L_{AC} are evaluated at room temperature, as shown in figure 3. In figure 3(a), the differential on-state resistance (R_{ON}) is calculated to be 4.3 Ω mm, 5 Ω mm, 6.2 Ω mm, 8.3 Ω mm and 13.6 Ω mm with an L_{AC} of 6 μm, 8 μm, 10 μm, 15 μm and 20 μm, respectively. V_T, which is defined as the voltage when the forward current reaches 1 mA mm^{-1}, is 0.57 V with a negligible variation for different values of L_{AC}. This V_T is similar to that of state-of-the-art AlGaN/GaN SBDs with Ni/Au as the Schottky metal [11, 14, 18]. In figure 3(b), the TB-GET SBDs with 10 nm SiN_x can reach a hard-breakdown voltage (@1 mA mm^{-1}) of 1.1 kV, 1.5 kV, 1.6 kV, 1.87 kV and 2.0 kV with an L_{AC} of 6 μm, 8 μm, 10 μm, 15 μm and 20 μm, respectively. On the other hand, the SBDs with this effective termination technique can successfully reduce the leakage current, and the voltage at 1 μA mm^{-1}

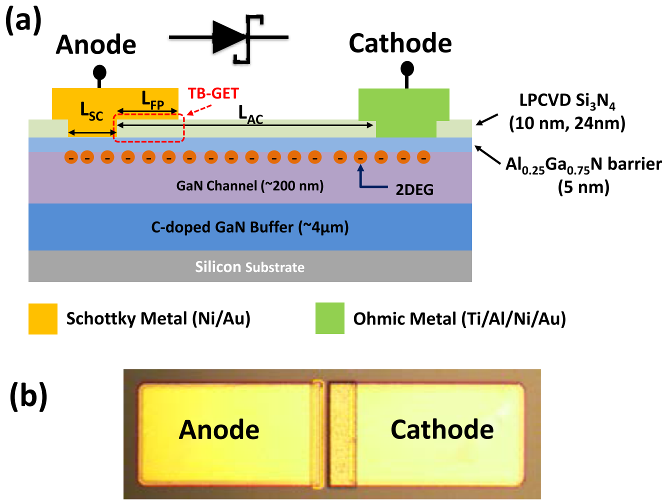

Figure 1. (a) Schematic cross-section of the recess-free TB-GET SBD and epistructure ($Al_{0.25}Ga_{0.75}N$ barrier is 5 nm), where L_{SC} and L_{AC} are the length of the Schottky contact region and the drift length of the SBD, respectively. (b) Photograph image of the fabricated device.

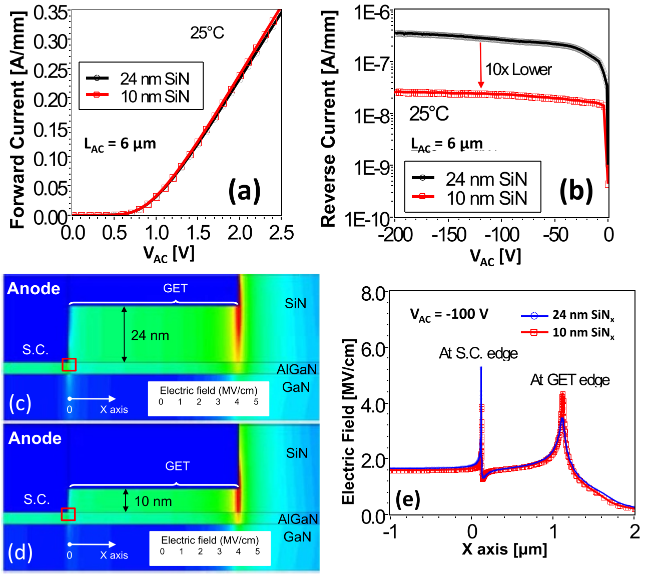

Figure 2. Typical (a) forward (b) and reverse I–V curves of the TB-GET SBDs with 24 nm and 10 nm LPCVD SiN_x, both with an anode finger width of 100 μm, $L_{SC} = 6$ μm and $L_{AC} = 6$ μm. 2D electric field simulation of the anode region at a reverse voltage of -100 V for SBD with (c) 24 nm SiN_x and (d) 10 nm SiN_x.
(e) Electric field distribution in the AlGaN barrier (0.5 nm below the anode contact) at a reverse voltage of -100 V for the SBD with two different SiN_x thickness.

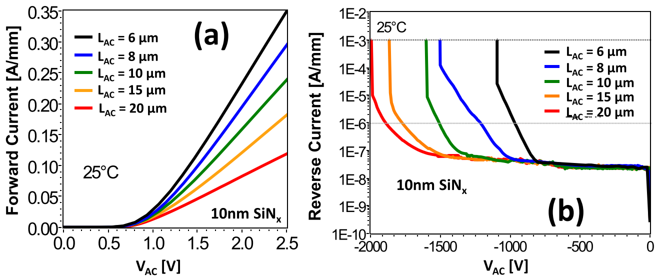

Figure 3. Typical (a) forward and (b) reverse leakage and breakdown characteristics of the TB-GET SBD (10 nm only) with a variation of anode-to-cathode spacing L_{AC}. The device dimensions are $L_{SC}/W = 6/100$ μm.

is 0.98 kV, 1.2 kV, 1.55 kV, 1.78 kV and 1.9 kV with an L_{AC} of 6 μm, 8 μm, 10 μm, 15 μm and 20 μm, respectively.

The temperature dependence of the forward and reverse characteristics is shown in figure 4. A negative temperature coefficient is observed in the forward current characteristics, and the 'thermal stable point' of the forward current is at a very low current level due to the current conduction being dominated by the tunneling mechanism [19], leading to fewer 'thermal runaway' problems [20]. At the same time, a temperature increase from 25 °C to 150 °C results in an increase in leakage by less than one order of magnitude.

An important feature of the recess-free TB-GET is that the turn-on voltage (V_T) is mainly determined by the as-grown AlGaN thickness, leading to high uniformity of the forward characteristics. The V_T statistics from 30 SBDs with

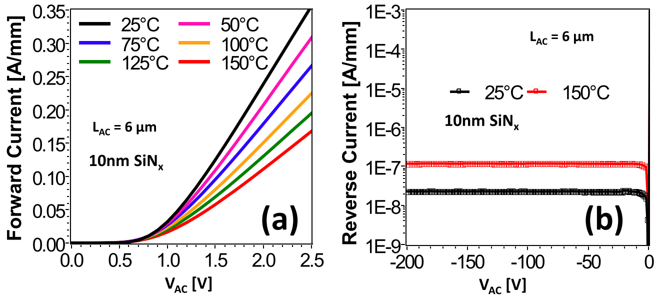

Figure 4. (a) Forward characteristics and (b) reverse leakage current for the recess-free TB-GET SBD (only with 10 nm SiN_x) at different temperatures. The device dimensions are $L_{AC}/L_{SC}/W = 6/6/100$ μm.

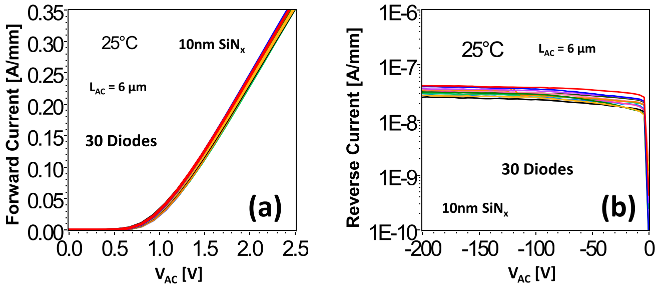

Figure 5. (a) Distribution of forward I–V characteristics of 30 devices. (b) Distribution of reverse leakage curves of 30 devices with $L_{SC} = 6$ μm, $L_{AC} = 6$ μm. The proposed TB-GET shows good uniformity over 4 inch wafer.

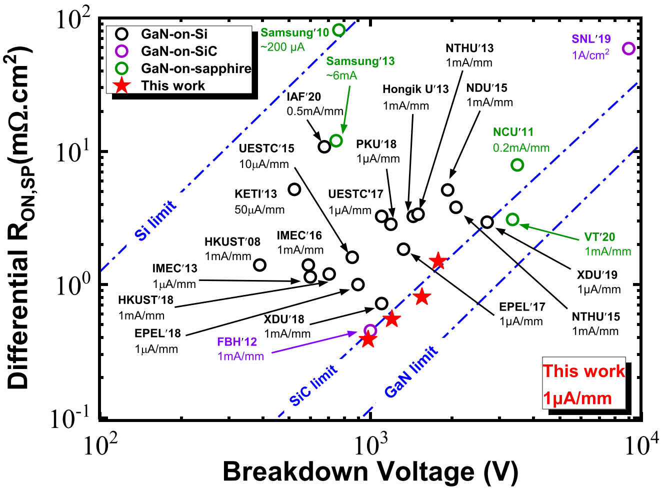

Figure 6. Benchmark of differential $R_{ON,SP}$ vs. BV of GaN diode on SiC/sapphire/Si substrates. The recess-free TB-GET SBD shows a low differential on-state resistance $R_{on,sp}$ of 1.49 mΩ cm^2 and a BV of 1780 V@1 μA mm^{-1} with $L_{AC} = 15$ μm.

an identical device layout at room temperature are shown in figure 5(a), exhibiting a tight distribution over the 4 inch wafer. Moreover, the reverse leakage is uniformly distributed between 20 and 40 nA mm^{-1} at -200 V as well, shown in figure 5(b), due to the elimination of the AlGaN barrier recess, leading to damage-free bombardment in the Schottky and GET regions.

The differential $R_{ON,SP}$ is calculated as the product of the normalized differential R_{ON} (Ω mm) and the total length of current flow, which is the sum of L_{AC} plus twice 1.5 μm, supposing the anode and cathode both have a 1.5 μm transfer length. Figure 6 shows the differential $R_{ON,SP}$ vs. breakdown voltage (BV) of the state-of-the-art GaN diode on different substrates. The recess-free TB-GET with an L_{AC} of 15 μm delivers a BV of 1780 V@1 μA mm^{-1} with a corresponding $R_{ON,SP}$ of 1.49 mΩ cm^2. This value is among the best results reported for a GaN-on-Si diode at a reverse leakage as low as 1 μA mm^{-1}.

3. Conclusion

High-performance recess-free TB-GET SBDs are fabricated on thin-barrier AlGaN/GaN heterostructures. Combined with effectively preserved 2DEG by LPCVD Si_3N_4 passivation and formation of GET termination to lower the reverse leakage without Schottky barrier recess, the SBD achieves a low turn-on voltage of 0.57 V with high uniformity, a low differential specific on-resistance $R_{ON,SP}$ of 1.49 mΩ cm^2, and a high reverse breakdown voltage of 1.78 kV@1 μA mm^{-1}. The proposed diode fabrication is compatible with the GaN depletion/enhancement MIS-HEMT process flow, and shows promise for integration in the smart GaN platform.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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