Article

The Influence of Anode Trench Geometries on Electrical Properties of AlGaN/GaN Schottky Barrier Diodes

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Abstract: AlGaN/GaN lateral Schottky barrier diodes (SBDs) with three different anode geometries (stripe, circular, and the conventional plane one) and different rows of anode trenches are fabricated and electrically characterized to study the influence of anode trench geometries. The SBDs with anode trenches exhibit the lower on-state resistance (R_{ON}) than that with the conventional plane one. It can be explained that the anode trenches made the Schottky metal directly contact to the 2DEG at the sidewall of the AlGaN/GaN interface, removing the AlGaN barrier layer in the conventional plane anode. In addition, the R_{ON} of the SBDs with circular trenches is smaller than that of the SBDs with stripe ones. Furthermore, the R_{ON} decreases with the increasing rows of anode trenches, which can be attributed to the increased contact area between the Schottky metal and the 2DEG. For the reverse characteristics, the anode trenches do not lead to performance degradation. The fabricated devices exhibit the low reverse current (I_R , $I_R < 1 \mu A/mm$), and the breakdown voltage (V_{BK}) remains unchanged with different anode geometries.

Keywords: GaN; Schottky barrier diode; breakdown voltage; anode trenches

1. Introduction

GaN is one of the most suitable material candidates for power electronics and has attracted tremendous research interests due to the unique material properties. Recently, the AlGaN/GaN heterostructures have been the subject of intense research for application in high-voltage/high-power electronic devices and optoelectronic devices [1,2]. GaN power devices can operate at high temperature, high voltage, and high speed thanks to the large bandgap, superior breakdown field strength, and excellent electron saturation velocity. Among GaN power devices, GaN diode rectifiers are indispensable devices in power switching applications, such as switch mode power supplies, converters, and inverters. AlGaN/GaN Schottky barrier diodes (SBDs), as one of the most popular members of the GaN rectifier family, are attracting great attention since they can be easily and monolithically integrated with GaN transistors [3]. However, conventional AlGaN/GaN SBDs suffer from large on-state resistance (R_{ON}) because the AlGaN barrier hinders the forward current. Approaches such as anode trench SBDs [4] and anode with dual metals [5,6] have been proposed to address the challenge. Among these methods, the anode trench technology is widely used in SBDs and reported in a number of literature. For example, anode trenches combined with carbon-doped GaN [7], AlGaN back-barrier [8], and field-plate structure [9,10] have been used to reduce the R_{ON} and improve the breakdown voltage (V_{BK}). 3D anode trenches combined with insulated tri-gate metal-oxide-semiconductor (MOS)

structure [11] or gated edge termination structure [12] have been reported to reduce the R_{ON} and realize an ultra-low reverse current (I_R). In addition, nano-patterned anode trenches have been fabricated in AlGaIn/GaN SBDs with a series of periodically spaced trenches [8] to reduce R_{ON} and I_R . Moreover, nanowire hybrid tri-anode and tri-gate structures present high V_{BK} and low R_{ON} [10–12]. However, there is little literature reporting the influence of anode trench geometry on the electrical properties of SBDs. In order to further improve the device performance in power applications, clarifying the effect of the anode geometries on the SBDs is one of the fundamental issues for anode trench SBDs.

In this letter, AlGaIn/GaN SBDs with three different anode geometries (stripe, circular, and the conventional plane one) and different rows of anode trenches are fabricated and electrically characterized to study the influence of anode trench geometries. R_{ON} is sensitive to the anode shapes. The SBDs with circular anode trenches possess lower R_{ON} than that with stripe anode trenches at the same number of rows. In addition, the more rows of anode trenches, the smaller the R_{ON} , which can be interpreted that the longer the perimeter, the larger the proportion of the Schottky metal directly in contact with the two dimensional electron gas (2DEG) at the sidewall of the AlGaIn/GaN interface. In addition, the anode trenches reduce the R_{ON} without sacrificing the reverse characteristics compared with the conventional plane one. In addition, the fabricated devices exhibit a low I_R ($<1 \mu\text{A}/\text{mm}$). Moreover, the V_{BK} is not degraded by the anode trenches.

2. Experiment

The epitaxial layers were grown by metal organic chemical vapor deposition (MOCVD) on a two-inch sapphire substrate [13], consisting of $2 \mu\text{m}$ high resistance GaN (HR-GaN), 100 nm undoped GaN (u-GaN) channel, 1 nm AlN, 25 nm undoped $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}$ (u- $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}$) barrier, and a 2 nm u-GaN cap layer. For comparison, three types of anode geometries were designed, which were the conventional plane, stripe, and the circular one. A cross sectional schematic of the fabricated anode trench SBD is shown in Figure 1a, and the top view of different anode geometries is shown in Figure 1b. The length and width of the stripe trench were fixed at $100 \mu\text{m}$ and $10 \mu\text{m}$, respectively. The spacing between the two adjacent stripe trenches was $5 \mu\text{m}$. The diameter of circular trenches was $10 \mu\text{m}$, with the other parameters the same as the stripe ones. In addition, the number of rows were changed from one to four for SBDs with anode trenches. The anode area of all samples was $120 \mu\text{m} \times 120 \mu\text{m}$. The distance between anode and cathode (L_{AC}) was set as $10 \mu\text{m}$, $15 \mu\text{m}$, and $20 \mu\text{m}$, respectively.

Figure 1. (a) schematic view of fabricated Schottky barrier diodes (SBD) with one type of the anode trenches; (b) the top view of three anode geometries, and the number of rows is changed from 1 to 4.

Device fabrication started with mesa isolation by using inductively coupled plasma (ICP) etching [14], and the depth was about 400 nm . Subsequently, the stripe arrays and circular arrays were patterned onto the samples. Then, the anode trenches were also accomplished by ICP etching down to the GaN channel layer with an etch depth of about 50 nm . Afterwards, the cathode metal consisting of Ti/Al/Ti/Au [15] ($20/100/50/70 \text{ nm}$) was deposited by electron-beam evaporation and annealed at 870°C for 30 s in nitrogen ambient [16]. After the formation of ohmic contact, a Ni/Au [17] ($100/50 \text{ nm}$)

metal stack was used for Schottky contact. Moreover, all devices were fabricated on the same wafer for fair comparison.

3. Results

The anode trench depth was about 50 nm measured by the Dektak Profilometer (Veeco Instruments Inc, Plainview, NY, USA). In Figure 2, the root-mean-square (RMS) surface roughness before and after etching was 0.357 nm and 0.362 nm, respectively, measured by a dimension 3100 atomic force microscope system (Veeco Instruments Inc, Plainview, NY, USA). Hence, the dry etching had little impact on the surface roughness. In addition, the cathode contact resistivity ρ_c of $4.45 \times 10^{-5} \Omega \bullet \text{cm}^2$ and sheet resistance R_{sh} of 359 $\Omega/\square$ were calculated by the transmission line method (TLM) based on measurement by a Keithley 4200 Semiconductor Characterization System (Tektronix Inc, Beaverton, USA).

Figure 2. Atomic force microscopy (AFM) images of the surface before etching and after etching of $5 \times 5 \mu\text{m}^2$.

Typical forward rectifying characteristics of SBDs with three different anode geometries (the conventional plane, stripe, and circular one) are compared in Figure 3a, with the number of trenches rows kept at 4 and $L_{AC} = 10 \mu\text{m}$. The forward I-V curves can be divided into three parts. When the forward voltage (V_F) ranges between 0 V and 0.3 V, the current is dominated by a recombination current. The recombination current may be related to carrier recombination at the GaN/metal interface. In this part, the SBDs with anode trenches have larger current than that of a conventional plane due to the larger surface recombination rate [18,19], as shown in the inset of Figure 3a. In the range between 0.3 V and 1.7 V, where the diffusion current dominates, the currents of SBDs with three anode geometries are almost the same, indicating that the devices with different anode geometries have the similar V_{ON} and Schottky barrier height (SBH). In the range between 1.7 V and 3 V, the current is determined by the series resistance. In this voltage range, the SBDs with anode trenches have a larger current than that of the conventional plane due to the reduced series resistance. For the SBDs with other trenches' rows, the I-V characteristics are similar.

Especially, we extracted the V_{ON} and R_{ON} of SBDs with different anode shapes and rows of anode trenches from the measured I-V curves, as shown in Figure 3b,c. The V_{ON} is obtained at the forward current (I_F) of 1 mA/mm [9,20], and the R_{ON} is the inverse of the slope of the I-V curves in the linear region, as shown in Figure 3a. The devices with different anode geometries have the similar V_{ON} between 0.8 V and 0.9 V. We guess the possible reason is that dry etching causes an increase in the metal/2DEG contact barrier, leading to the similar contact barrier of metal/2DEG and metal/AlGaN [21,22]. In contrast to V_{ON} , R_{ON} is sensitive to the shapes of anode trenches. The SBDs with anode trenches have the lower R_{ON} compared with conventional plane ones because the anode trenches make the Schottky metal in direct contact with the 2DEG [4,6], removing the AlGaN barrier layer in the conventional plane. The R_{ON} of the SBDs with circular trenches is smaller than that of the SBDs with stripe ones because the circular trenches have the larger perimeter, causing the larger contact area at the metal/2DEG interface and the more current flows through the Schottky interface. In addition, as the rows of anode trenches increased, the R_{ON} decreased, which is due to the further

increase of the contact area. Figure 3d shows the relationship between the perimeter and R_{ON} . It shows that R_{ON} decreases monotonically with the perimeter.

Figure 3. (a) the forward characteristics of the SBDs with three different anode geometries (with four rows of circular anode trenches and $L_{AC}=10 \mu m$). Inset: log scale of the forward-bias regime. The dash line in (a) illustrates the definition of R_{ON} used in this letter; (b) the V_{ON} ($I_F=1 \text{ mA/mm}$) of SBDs with three different anode geometries vs. number of rows. (The conventional plane has 0 rows of anode trenches); (c) the R_{ON} of SBDs with different anode geometries vs. number of rows; (d) the R_{ON} of SBDs with different perimeters of anode trenches (The perimeter of the conventional plane is $0 \mu m$).

Figure 4a shows the reverse characteristic curves of SBDs with three different anode geometries (the conventional plane, stripe, and circular one), with the row of trenches kept at 4 and $L_{AC} = 10 \mu m$. All of the devices have the extremely low reverse leakage current I_R ($<0.1 \mu A/mm$) at the initial $0 \sim -150 \text{ V}$ and then slowly increase with the reverse voltage until breakdown at around 410 V . Especially, I_R and V_{BK} with different rows are extracted from the I-V curves, as shown in Figure 4b,c. The V_{BK} is obtained at the reverse current of 1 mA/mm . In addition, the I_R is the reverse current at the reverse voltage of 200 V . The I_R of the devices is between 6×10^{-8} and $1 \times 10^{-7} \text{ A/mm}$ ($<1 \mu A/mm$) for all devices, implying that I_R is independent of shapes and rows of anode trenches. It indicates that no obvious lattice damage and deteriorated leakage current were introduced by the etching process. Therefore, the trench structures may not cause significant degradation of the reliability. The possible reason is that the forward current path is from the sidewall Schottky contact of the anode trench. However, a proper reverse bias makes the 2DEG completely depleted, and the currents tunneling through the sidewall Schottky contact are blocked. Consequently, the reverse current path mainly ran through the overlapped planar Schottky contact. Accordingly, the I_R of SBDs with anode trenches is not sacrificed compared with conventional plane [23]. Figure 4c shows that the V_{BK} of all the devices is between 400 V and 425 V . There is no noticeable difference observed between the conventional plane and trench structures, meaning that V_{BK} was not degraded by the anode trenches [6].

The typical forward bias characteristics of SBDs with different L_{AC} are compared in Figure 5a. The anode shape is selected as a circle, and the row of the anode trench is 4. I_F ($V_F = 3 \text{ V}$) decreases with the increase of L_{AC} , indicating that R_{ON} decreases with the increase of L_{AC} . The V_{ON} and R_{ON} of SBDs with different L_{AC} and row numbers are extracted from I-V curves, as shown in Figure 5b,c. Figure 5b depicts the V_{ON} as being practically independent of L_{AC} [9,24,25]. Figure 5c shows the R_{ON} naturally

scales with L_{AC} , which is consistent with reported literature [20]. Consequently, the R_{ON} is mainly related to the series resistance. The longer the L_{AC} , the larger the series resistance. Figure 5d shows the V_{BK} of the fabricated diodes with various L_{AC} . The higher the L_{AC} , the more pronounced is the reverse blocking capability of the SBDs [5,13,14]. This led to the well-known tradeoff between R_{ON} and V_{BK} . Because all the devices are not passivated, the V_{BK} of the devices are not increased significantly.

Figure 4. (a) the reverse-bias log scale (absolute values) two-pole characteristics for the SBDs with three different anode geometries (with four rows of circular anode trenches and $L_{AC}=10\ \mu\text{m}$); (b) the I_R (at reverse voltage up to 200 V) for the SBDs with three different anode geometries ($L_{AC}=10\ \mu\text{m}$) vs. rows of anode trenches; (c) the V_{BK} for the SBDs with three types of anode geometries ($L_{AC}=10\ \mu\text{m}$) vs. rows of anode trenches.

Figure 5. (a) the forward characteristics of the SBDs (with four rows of circular anode trenches) with different L_{AC} ; (b) the V_{ON} of SBDs (with four rows of circular anode trenches) with different L_{AC} ; (c) the R_{ON} of the SBDs (with four rows of circular anode trenches) with different L_{AC} ; (d) the reverse-bias log scale (absolute values) two-pole characteristics for the SBDs (with four rows of circular anode trenches) with different L_{AC} .

4. Conclusions

In conclusion, anode AlGaIn/GaN SBDs with three different anode geometries (the conventional plane, stripe, and circular one) have been fabricated. The SBDs with anode trenches possess lower R_{ON} compared with conventional plane one. In addition, the SBDs with circular anode trenches enjoy lower R_{ON} than that with stripe anode trenches at the same number of rows. Furthermore, the perimeter increases with the increase in the number of anode trenches because the proportion of the Schottky metal directly in contact with the 2DEG at the sidewall of the AlGaIn/GaN interface increases, leading to a reduced R_{ON} . In addition, the SBDs with anode trenches exhibit reduced R_{ON} without sacrificing the reverse characteristics compared with the conventional plane. Furthermore, the fabricated devices exhibit a low I_R ($<1 \mu A/mm$) and the V_{BK} is not degraded by the anode trenches.

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