Research Article
AlGaN/GaN Heterostructure Schottky Barrier Diodes with Graded Barrier Layer

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AlGaN/GaN Schottky barrier diodes (SBDs) working as high-power mixer and multiplier show great potential in millimeter wave (MMW) field owing to their high breakdown voltage. Nevertheless, its further application is severely limited by large reverse leakage current \( J_r \) since the two-dimensional electron gas (2DEG) channel is hard to be pinched off at low voltage. To address this limitation, a graded AlGaN/GaN heterostructure is introduced to extend the 2DEG channel into a quasi-three-dimensional electron slab. By comparing the fixed Al composition AlGaN/GaN SBD, \( J_r \) of the graded AlGaN/GaN SBD is significantly reduced due to the extension of channel carriers, confirming the effective \( J_r \) suppression effect of this structure. Furthermore, on this basis, a recessed anode structure is utilized to expect a smaller \( J_r \). The results indicated that the graded AlGaN/GaN SBDs with air-bridge structure have achieved a pretty low \( J_r \) value \((1.6 \times 10^{-13} \text{ A at -15 V})\), and its cutoff frequency is as high as 60.6 GHz. It is expected that such SBDs with low \( J_r \) have significant advantages in future applications.

1. Introduction

The Schottky barrier diodes (SBDs) can be used as mixer and multiplier elements in millimeter wave (MMW) imaging [1, 2], nondestructive testing [3], automotive sensors [4, 5], and communication [6] regions due to their nonlinear effect and mature manufacturing technology [7–11]. To date, the planar GaAs-based SBD is still the most commonly used element, but it always exhibits large reverse leakage currents \( J_r \) and low breakdown voltage, which seriously limits its applications in the high-power field [9]. By contrast, GaN-based SBDs have a higher breakdown voltage and show greater application advantages in the MMW field. Specifically, some researchers have achieved high breakdown voltage and high cutoff frequency \( f_c \) with the n−-GaN/n+ -GaN structure [12, 13]. In our previous studies, we also have reported the breakdown voltage of -20 V at 0.1 µA and a \( f_c \) of 114 GHz based on AlGaN/GaN heterostructure [14]. Compared to bulk doping, the two-dimensional electron gas (2DEG) with high electron mobility and high carrier concentration can be acquired at AlGaN/GaN interface due to its spontaneous polarization and piezoelectric polarization [15–17]. However, according to related reports, the SBDs based on the AlGaN/GaN heterostructure exhibit large \( J_r \) because the 2DEG channel is hard to be pinched off at low voltage [18–21]. To solve this problem, an extended 2DEG structure was designed by the graded AlGaN/GaN heterostructure [22–25]. The graded AlGaN/GaN exhibits high...
mobility compared with bulk doping due to the removal of ionized impurity scattering, especially in low-temperature environments [22]. Furthermore, the graded AlGaN/GaN can realize better stability due to the robustness of surface states [24]. However, the characteristics of the graded AlGaN/GaN SBDs are rarely reported, and investigations about leakage properties are still lacking.

In this work, the planar SBDs based on the fixed Al component AlGaN/GaN and the graded AlGaN/GaN heterostructures were fabricated, and their current-voltage (I-V) and capacitance-voltage (C-V) characteristics were evaluated and compared. The carrier distribution of the graded AlGaN/GaN heterostructures was analyzed according to the simulated and experimental results, which supported the extension of the carrier distribution. The forward and reverse currents of SBDs were also studied through the structures with and without recessed anode. As a result, the SBDs with the air-bridge structure have achieved a pretty low $f_r$ value using graded AlGaN/GaN; meanwhile, the $f_r$ is as high as 60.6 GHz.

2. Experiments

The samples of graded AlGaN/GaN heterostructures were grown on a c-plane sapphire substrate by metal-organic chemical vapor deposition (MOCVD). The sample structures consist of a 20 nm AlN nucleation layer, a 2.5 μm C-doped (4 × 10¹⁹ cm⁻³) GaN buffer layer, a 200 nm unintentionally doped (UID) GaN, and a 35 nm graded AlₓGaₙ₋ₓN/GaN barrier layer. C-doped GaN buffer layer is semi-insulating, which avoids the leakage current of the buffer layer and reduces the parasitic capacitance. Si concentration of UID GaN is lower than 10¹⁶ cm⁻³. The Al component $x$ of graded AlₓGaₙ₋ₓN/GaN barrier layer from UID GaN to the surface is changed from 0 to 0.27 (S1) and from 0 to 0.35 (S2), as shown in Figure 1(a). In order to compare with the conventional AlGaN/GaN SBDs, a 35 nm fixed Al component Alₓ=0.35Ga₀.₆₅N/GaN barrier heterostructure (S3) was designed, as shown in Figure 1(b). The distribution of Ga and Al composition in the S2 was measured by secondary ion mass spectroscopy (SIMS), as shown in Figure 1(c). It can be seen that the Al composition is graded from UID GaN to Alₓ=0.35Ga₀.₆₅N surface, which extends the carrier distribution in the channel.

In order to verify the carrier distribution in the graded AlGaN barrier layer, the ring SBDs were fabricated with three steps. (1) The device mesa isolation of 300 nm was performed by dry etching using inductively coupled plasma (ICP). (2) The cathode ohmic metals of Ti/Al/Ni/Au (15/80/20/60 nm) were deposited by E-beam and thermal evaporator followed by rapid thermal annealing (RTA) at 850°C for 30 s in N₂. (3) The metals of Ni/Au (20/80 nm) were deposited in an anode. The schematic of their structures are illustrated in Figures 2(a) and 2(b). In conventional ring SBD, the anode radius (R) is 100 μm, and the space ($I_{th}$) between the cathode and anode electrode is 20 μm. In recessed ring SBD, the recess radius ($r$) is 99 μm, which effectively reduces the capacitance of the ring SBD. Parts of anode metals were designed to be overlapped on the sample surface because the radius of the recess is less than the anode metal. The parallel connection of overlapped planar and recessed sidewall Schottky diode is formed in SBD with the recessed anode. Figure 2(c) shows an optical microscope photograph of ring SBD. The SBD with air-bridge structure was designed to improve $f_r$. The gold air-bridge which connected the small anode and electrode pad was fabricated using the electroplating technique. The structural parameters of the SBD with air-bridge structure are as follows: $R = 4 \mu m$, $r = 3.95 \mu m$, and $L_{sc} = 2 \mu m$. The reduction of anode size can effectively increase the $f_r$. Figures 2(d) and 2(e) show the schematic structure and SEM image of the SBD with air-bridge structure, respectively.

The C-V characteristics were measured with alternating voltage of 30 mV amplitude and 1 MHz frequency by Keysight E4980 A LCR meter. The I-V characteristics were tested by Keithley 4200-SCS semiconductor parameter analyzer. All tests were performed at room temperature.

3. Results and Discussion

In order to obtain the characteristics of carrier concentration vs. depth in the graded AlGaN/GaN heterostructure, the C-V characteristics of the conventional ring SBDs and the recessed ring SBDs were measured, as shown in Figures 3(a) and 3(b). It is observed that the capacitance of recessed ring SBDs is reduced by two orders of magnitude compared with the conventional ring SBDs, which is attributed to the sharp reduction of the effective area of the parallel plate capacitor. Theoretically, the capacitance of conventional ring SBD can be described as a parallel plate capacitor with a depletion width ($W = \varepsilon_0 \varepsilon_r A/C$), where $\varepsilon_0$, $\varepsilon_r$, $A$, and $C$ represent the vacuum dielectric constant, the dielectric constant of AlGaN, the anode area, and the capacitance of reverse-bias junction, respectively. The function of carrier concentration ($N_A$) vs. depth is described by the following equation [26]:

$$N_A(W) = \frac{1}{d(1/C^2)/dV} \cdot \frac{2}{q\varepsilon_0\varepsilon_r A^2},$$

where $q$ is the elementary charge. Based on this, the carrier distributions of S1, S2, and S3 were calculated and plotted in Figure 3(c). For S3, its carrier distribution width is the smallest and is quantified as 1.1 nm, which is much narrower than S1 (5.8 nm) and S2 (6.0 nm). Furthermore, it also has the largest carrier concentration ($1.04 \times 10^{20}$ cm⁻³) compared to S1 (1.37 × 10¹⁹ cm⁻³) and S2 (1.37 × 10¹⁹ cm⁻³). As for S1 and S2, it can be concluded that their carrier distribution is significantly extended to quasi 3-D electron slab in the graded AlGaN barrier layer. Additionally, the capacitance of S3 is smaller than those of S1 and S2 because the channel carriers are farther away from the anode metal. Consequently, S3 ($V_{S3} = -6.5$ V) shows a higher pinch-off voltage of depleted channel carriers compared with S1 ($V_{S1} = -2.8$ V) and S2 ($V_{S2} = -3.2$ V) owing to the higher carrier concentration and deeper carrier position.

Figure 3(d) shows the band structure versus the depth based on simulation results. The potential well is extended...
from AlGaN/GaN interface to the graded AlGaN barrier layer. Figure 3(c) shows the carrier distribution versus the depth, which is similar to the carrier distribution by C-V calculation. In order to investigate the extension of the carrier distribution, the distribution of polarization charge along the [0001] direction was calculated by the Poisson equation [27].

\[
\nabla \left[ \left( \varepsilon_z + \frac{c_z^2}{c_z} \right) \nabla \phi \right] = -\rho + \nabla \cdot P_z, \tag{2}
\]

where \(\varepsilon_z\) is permittivity, \(c_z\) is the piezoelectric coefficient, \(c_z\) is elastic constant, \(P_z\) is the total polarization in the material, \(\phi\) is the electrostatic potential, and \(\rho\) is the charge distribution. The parameters of \(\varepsilon_z, c_z, c_z, \text{ and } P_z\) are all in [0001] direction. The polarization charge density of the S1 and S2 is significantly reduced by two orders of magnitude compared with S3, demonstrating the extension effect of the graded AlGaN barrier layer on the positive polarization sheet charge at the AlGaN/GaN interface, as shown in Figures 3(e) and 3(f).

Figures 4(a) and 4(b) exhibit good Schottky diode properties of conventional and recessed ring SBDs. When the voltage is lower than the pinch-off voltage \((V_S < V_r < 0 \text{ V})\), the currents gradually increase as the voltage increases due to the Frenkel-Poole (FP) emission mechanism [21, 28–30], and the channel carriers are not pinch-off at this time. In comparison with the S2 and S3, the S1 increases more slowly due to the thicker barrier width. When the voltage is higher than the pinch-off voltage \((V_r < V_S)\), the currents reach saturation thanks to the pinch-off of channel carriers, and in this range, \(J_r\) is mainly due to the emission mechanism based on trap-assisted tunneling (TAT). Compared with the fixed Al composition AlGaN/GaN SBD, the saturated \(J_r\) of the graded AlGaN/GaN SBD is reduced due to the lower carrier concentration, wider depletion width, and lower tunneling probability. Moreover, the channel is more likely to be pinched off at lower reverse-bias
voltage due to shallow carrier distribution. In addition, we found that the saturated $I_r$ values are a linear relationship with the effective anode area and are related to the trap concentration on the AlGaN surface [21]. In comparison with conventional rings SBDs, the saturated $I_r$ values of recessed rings SBDs are reduced by about three orders of magnitude, which is contributed to the smaller effective anode area.

The electrical characteristics are summarized in Table 1. The ideality factor of SBDs is larger than 1, which indicates that the transport mechanisms include TAT, recombination, and thermionic emission (TE) under the forward voltage.

![Figure 3: The C-V characteristics of (a) conventional and (b) recessed ring SBDs. (c) The carrier concentration vs. depths of S1, S2, and S3 by experiment and simulation. (d) The $E_C$ energy level vs. depths of S1, S2, and S3. The distribution of polarization charge of (e) S1 and S2, and (f) S3.](image)

![Figure 4: The I-V characteristics of (a) conventional and (b) recessed ring SBDs.](image)
The series resistance ($R_s$) of recessed ring SBDs is larger than conventional ring SBDs because the electrons laterally flow to the anode metal of the recessed sidewall. In comparison with conventional rings SBDs, the $f_c$ of the recessed rings SBDs is improved by two orders of magnitude, as shown in Table 1.

The $f_c$ of SBD is a very important parameter in MMW regions, which is defined as $f_c = 1/(2\pi R_s C_0)$ [34]. The reduction of $R_s$ or $C_0$ is the only way to improve the $f_c$. In order to obtain a higher $f_c$, the SBD with an air-bridge structure is designed. The C-V and I-V characteristics are shown in Figures 5(a) and 5(b), respectively, which exhibit good Schottky diode properties. The value of $J_r$ between the two pads is about $2.8 \times 10^{-14}$ A. The electrical characteristics are described in Table 1. In comparison with the SBD of S3, the $J_r$ value of S2 is reduced by two orders of magnitude due to the extension of carriers in the channel. The capacitance of S3 is slowly decreased due to the sidewall capacitance of the recessed SBD device, as shown in Figure 5(b). The S2-based SBD with air-bridge structure shows $R_s$ of 210 $\Omega$, $C_0$ of 12.5 $fF$, $f_c$ of 60.6 GHz, and $J_r$ of $1.9 \times 10^{-12}$ A at -15 V.

The $J_r$ of the air-bridge structure planar SBDs is summarized in Figure 6. Compared with traditional GaAs-based SBDs, the GaN-based SBDs show a much higher breakdown voltage. What's more, the AlGaN/GaN SBDs show lower $J_r$ values. In this work, the graded AlGaN/GaN SBDs with the air-bridge structure have achieved the lowest $J_r$ values of $1.6 \times 10^{-13}$ A at -15 V, which can effectively reduce the heating of the device in mixer and multiplier.

| Sample | Size (μm) | Sample | Identities factor | Series resistance (Ω) | Saturated $J_r$ at -15 V (A) | Capacitance at 0 V (fF) | Cutoff frequency (GHz) |
|--------|----------|--------|-------------------|-----------------------|-----------------------------|------------------------|------------------------|
| S1     | 100, r = 0 | 1.64   | 51.5              | $1.0 \times 10^{-6}$  | 146 fF                      | 0.021                  |
| S2     | 1.68     | S3     | 1.53              | 21.5                  | $5.9 \times 10^{-5}$        | 109 fF                | 0.067                  |
|        |          |        |                   |                       |                             |                        |                        |
| S1     | 100, r = 99 | 1.34  | 105.8             | $1.2 \times 10^{-9}$  | 1.44 fF                     | 1.04                   |
| S2     | 1.33     | S3     | 1.95              | 20.5                  | $9.9 \times 10^{-8}$        | 1.25 fF               | 6.26                   |
|        |          |        |                   |                       |                             |                        |                        |
| S1     | 4, r = 3.95 | 1.89  | 368               | $1.6 \times 10^{-13}$ | 10.4 fF                     | 41.7                   |
| S2     | 1.94     | S3     | 2.19              | 151                   | $3.4 \times 10^{-10}$       | 11.5 fF               | 91.6                   |

Figure 5: The (a) I-V and (b) C-V characteristics of the air-bridge structure planar SBDs.
Reverse leakage current (A)

-22 -20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0

Ref. 13 n’-GaN/n’-GaN
Ref. 12 n’-GaN/n’-GaN
Ref. 14 AlGaN/GaN

This work AlGaN/GaN
This work Graded Al0.35GaN/GaN
This work Graded Al0.27GaN/GaN

Figure 6: The \( J_r \) values of the air-bridge structure planar SBDs.

4. Conclusions

In summary, the characteristics of the graded AlGaN/GaN SBDs with and without recessed anode have been evaluated by the I-V and C-V. The carrier distribution of the graded AlGaN/GaN heterostructures was analyzed using the Poisson equation, which reveals the reasons for the extension of the carrier distribution. Compared with the fixed Al component AlGaN/GaN SBD, the \( J_r \) is reduced by two orders of magnitude due to the extension of the carrier distribution. The graded AlGaN/GaN SBDs with air-bridge structure have achieved a pretty low \( J_r \) value \((1.6 \times 10^{-13} \text{ A})\) at \(-15 \text{ V}\). The \( f_c \) of graded Al0.35GaN/GaN SBD with air-bridge structure is 60.6GHz, and the \( I_r \) is as small as \(1.9 \times 10^{-12} \text{ A}\) at \(-15 \text{ V}\). These are beneficial to the applications of MMW in the future.

Data Availability

The data that were used to support this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest to disclose.

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