A revised approach to Schottky parameter extraction for GaN HEMT*

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Abstract: We carry out a thermal storage research on GaN HEMT at 350 °C for 48 h, and a recess phenomenon is observed in the low voltage section of Schottky forward characteristics. The decrease of 2DEG density will be responsible for the recess phenomenon. Because the conventional method is not suitable for this kind of curve, a revised approach is presented by analyzing the back-to-back Schottky junction energy band to extract Schottky parameters, which leads to a consistent fit effect.

Key words: AlGaN/GaN HEMT; 2DEG; thermal storage; back-to-back Schottky model
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1. Introduction

With the development of GaN HEMT, the reliability evaluation of it is deepening[1]. It is especially significant to research how to reasonably extract and analyze device parameters and the Schottky parameter is one of the basic parameters. Since 1979, Norde[2] and Cheung[3] have developed E.H.RHODERICK's extraction method. The low voltage section of the previous Schottky forward characteristics is linear, followed by a smooth arc high voltage section. Until 1988, Chen[4] found that the previous model could not meet the extraction to the HEMT Schottky parameter, when he studied AlGaAs/GaAs HEMT. Then he brought forward a back-to-back model to explain it. However, we discovered a new change in Schottky characteristics after thermal storage. The conventional I–V standard method could not deal with the new situation.

In this paper, we carry out an in-depth study on the Schottky curve, and believe that the decrease of 2DEG density results in recess phenomenon. A revised approach to extract Schottky parameters has been brought forward by analyzing the energy band. It is applied to evaluate the Schottky junction reliability of annealed devices, and makes sense of the research on GaN HEMT reliability.

2. Samples and research

The n-type GaN epitaxial films were grown on a SiC substrate by low-pressure metal-organic-chemical-vapor deposition (MOCVD). The epi-structure was i-AlGaN (5 nm)/n-AlGaN (10 nm)/i-AlGaN (6 nm)/AlN (1 nm)/i-GaN (2 μm)/SiC. The aluminum mole fraction in all AlGaN layers was 30%. The fabrication process for the Ohmic contact began with Ti/Al/Ni/Au Ohmic metallization and subsequent rapid thermal annealing at 870 ℃ for 30 s. Then a Schottky contact which consisted of Ni/Au was formed and the gate-recessed structure was adopted in this sample with an 8 nm recess-etched depth. At last, SiN film was deposited as a passivation layer using PECVD. The device was fabricated using a 10 finger structure with 100 μm for each finger, and the length of gate was designed as 1 μm, the source/drain spacing 4.5 μm.

The sample was put into an oven with a quartzose boat holding. The research was carried on at 350 ℃ for 48 h in N_2 ambient. Electrical measurements were carried out at room temperature after thermal storage using an Agilent 4155A parameter analyzer for current–voltage (I–V) characterization.

3. Analysis and approach

The typical semilog I–V characteristics for the annealed device are shown in the main figure of Fig. 1. The downward trend of the Schottky curve shows a decrease in the reverse leakage current of Schottky diodes and an increase in turn-on voltage. However, the obvious difference from previous re-

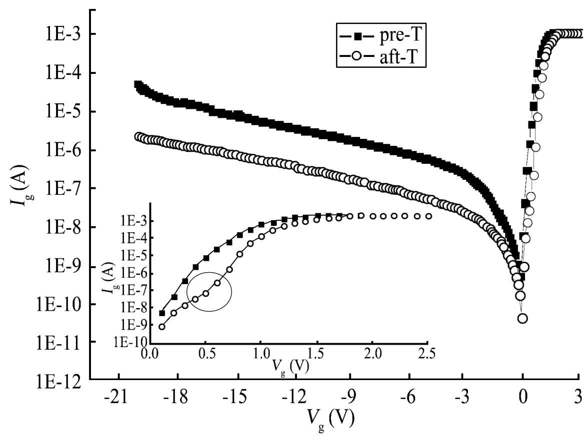

Fig. 1. I–V characteristics of Schottky diodes: before (square) and after (circle) thermal storage.

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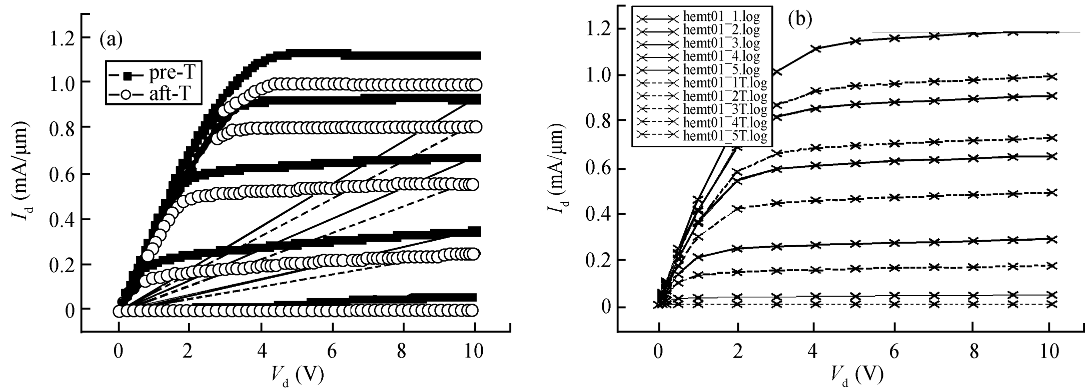

Fig. 2. Output characteristics of HEMT. (a) Measured: before (square) and after (circle) thermal storage. (b) Calculated: before (solid) and after (dashed) decreasing 2DEG density.

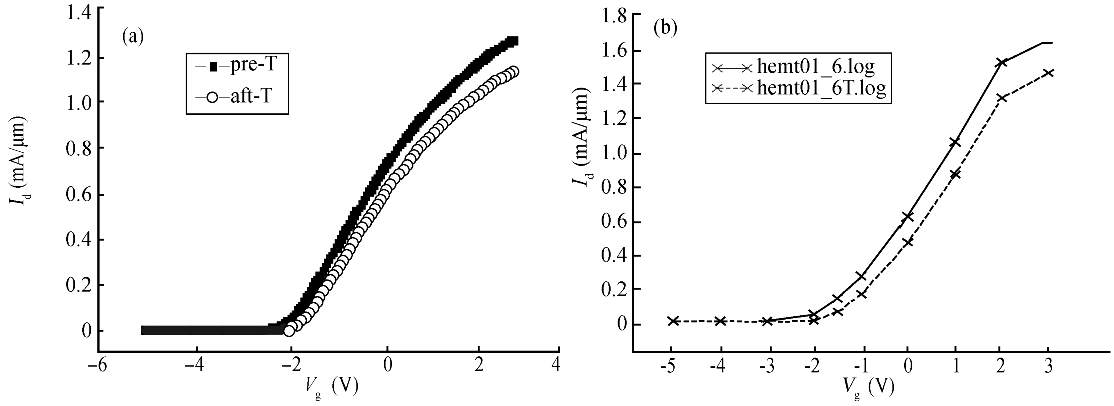

Fig. 3. Transfer characteristics of HEMT. (a) Measured: before (square) and after (circle) thermal storage. (b) Calculated: before (solid) and after (dashed) decreasing 2DEG density.

ports is that a recess was found in the Schottky curve around 0.5 V after thermal storage as shown on the set-in of Fig. 1. GaN Schottky characteristics before thermal storage show little difference with the conventional one. The conventional extraction method will be adequate for the demand but when the recess phenomenon appears, it is very difficult to select the linear section to extract the Schottky parameters. Therefore it is necessary to give a deep analysis of the recess, and bring forward a new approach to revise the $I-V$ standard method, which makes sense of the GaN HEMT reliability research.

3.1. Analysis of recess phenomenon

As was concluded by other researchers[5], the 2DEG density decreased after thermal storage or anneal according to the positive shift of 2DEG threshold voltage. We also observed some decrease in the current between the transmit line pad which indicated the electron concentration of 2DEG had decreased after thermal storage. We simulated output characteristics (Fig. 2) and transfer characteristics (Fig. 3) with variable 2DEG density by Silvaco TCAD software. The simulation results were consistent with the data measured. The structure adopted by simulations was the same as the samples. The 2DEG density was adjusted from 1×10^{13} cm^{-2} to 9×10^{12} cm^{-2} to imitate the degradation behavior. As was shown from the figures, $R_{\rm on}$ increased whether devices were annealed or 2DEG density decreased, and the threshold voltage gave a positive shift. To some extent, the decrease of 2DEG density accorded with the physical phenomenon.

Actually, as was said in Chen's model[4], GaN Schottky structure consists of two diodes in series. One is the metal–semiconductor (AlGaN) Schottky diode (diode 1), and the other is the equivalent Schottky diode (diode 2) due to the heterojunction between the AlGaN and GaN. 2DEG is equal to metal. If we apply a positive voltage at the gate and ground the 2DEG, the Schottky (metal–AlGaN) diode is forward biased and the other diode (AlGaN–GaN) interface is reverse biased. Before thermal storage, the 2DEG density was comparatively high. You can find that $E_{\rm f}$ was at a high level from the equation:

$$E_{\rm c} - E_{\rm f} = (kT/q)\ln(N_{\rm c}/N_{\rm d}). \tag{1}$$

Therefore, the restricting-current ability of diode 2 was not obvious due to the small equivalent Schottky barrier height ϕ_2 (shown in Fig. 4(a) below); after thermal storage, the 2DEG density decreased which increased ϕ_2. The restricting-current ability began to impact on Schottky characteristics now. When the voltage comes to a certain level, the current began to saturate. It is the key reason for the recess phenomenon.

3.2. New approach to extract Schottky parameters

Chen brought forward a back-to-back Schottky diode model to explain the restricting-current phenomenon as was mentioned above[4]. However, due to the different physical

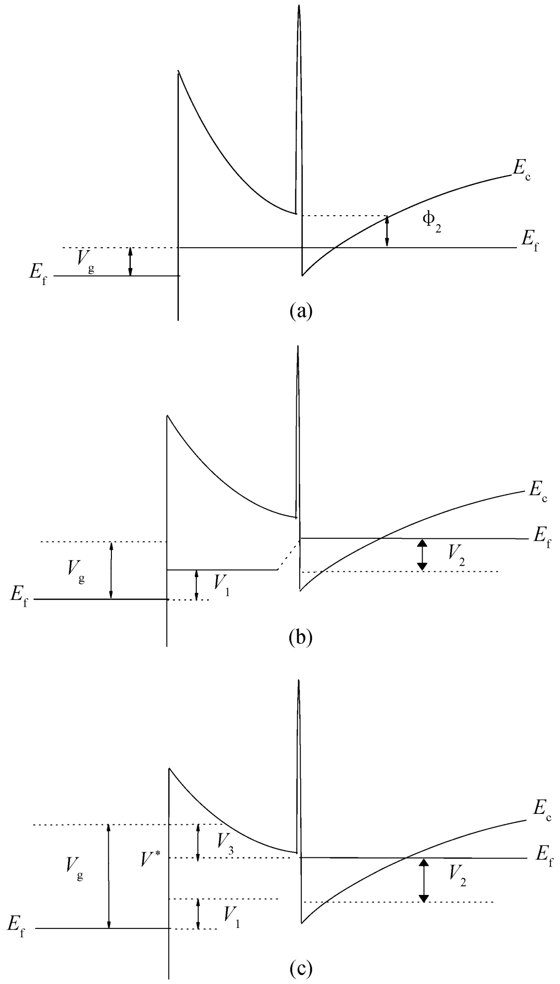

Fig. 4. Energy band of back-to-back Schottky diode with insertion of AlN. (a) Low voltage. (b) Diode 2 begins to restrict current. (c) Current begins to hoik.

properties, the linear section after current was restricted was not obvious in his time. It happens that this linear section is a true reflection of diode 1. According to the energy band (Fig. 4), we advance a new approach to extract Schottky parameters after thermal storage.

Figure 4 shows the change rule of Schottky energy band when the diode is forward-biased with the increasing voltage. When the voltage comes to V^*, the Fermi level is close to, or even equal to barrier peak value. The barrier cannot effectively restrict current, and the current can flow across Schottky junction smoothly. The further voltage (V_3) will drop across diode 1 instead. Therefore, we consider the high voltage linear section to be the true reflection of diode 1. We can obtain the parameter n_1' and ϕ_1' from this linear section, but we must awake to the fact that ϕ_1' has mixed the influence of diode 2. In order to eliminate this influence, we tried to derive a formula.

In Chen's model[4], the gate current of diode 1 can be expressed as

$$I_{gs} = I_{s1}[\exp(qV_1/n_1kT) - 1], \tag{2}$$

where

$$I_{s1} = AA^*T^2\exp(-q\phi_1/kT). \tag{3}$$

The gate current of diode 2 can be expressed as

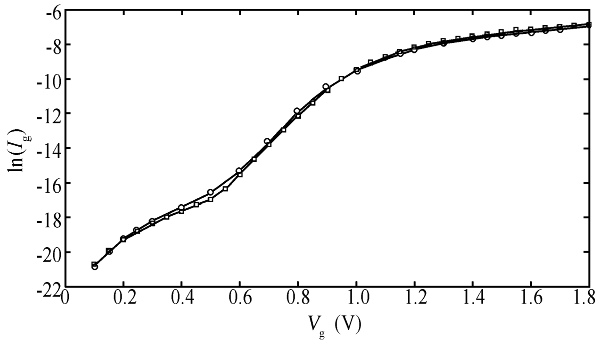

Fig. 5. Comparison of measured (circle) and fitted (square) line of forward I–V characteristics.

$$I_{gs} = I_{s2}[\exp(qV_2/n_2kT) - 1], \tag{4}$$

where

$$I_{s2} = AA^*T^2\exp(-q\phi_2/kT). \tag{5}$$

The gate–source voltage across the whole diode can be expressed as

$$V_{gs} = V_1 + V_2 + I_{gs}R_s. \tag{6}$$

Note that ϕ_1 is the barrier height of diode 1 at zero bias, and ϕ_2 diode 2. As is shown from Fig. 4(c), when the current begins to hoik, the gate current can also be expressed as

$$I_{gs} = AA^*T^2\exp(-q\phi_1/kT)\left[\exp\left(qV_{gs} - V_2\right)/n_1'kT) - 1\right]. \tag{7}$$

If

$$V_{gs} - V_2 \geqslant 3n_1'kT, \tag{8}$$

then

$$\phi_1 = kT\ln(AA^*T/I_{gs0}') - eV_2/n_1' = \phi_1' - eV_2/n_1'. \tag{9}$$

Now, the fitted line of high voltage linear section will give n_1' as the slope and I_{gs0}' as the y-axis intercept. ϕ_1 is the true barrier height, and the voltage V_2 can be calculated from Chen's model[4]. Or you can translate the fitted line to the low voltage section through the current point corresponding to 0.1 V. ϕ_1 is obtained by the formula

$$\phi_1 = kT\ln(AA^*T/I_{gs0}), \tag{10}$$

where I_{gs0} is the y-axis intercept, A is the diode gate area, A^* is the effective Richardson constant, k is Boltzrnann's constant, and T is the temperature.

The assumption of choosing linear section for I–V standard method is

$$V \geqslant 3kT/q. \tag{11}$$

Thus, the voltage of the first point must be after 0.077 V. Choosing the voltage of 0.1 V not only meets the condition, but also gives a small error. It is convenient to set up the sweep step of Agilent 4155A parameter analyzer. The result calculated by two ways has good coherence with an error of 0.002 eV. The value of ϕ_2 = 0.55 eV is extracted by Chen's model, and the value of ϕ_2 = 0.61 eV is obtained by the energy band simulation[6]. The corresponding structure consists of AlGaN/AlN/GaN with 30% Al content in AlGaN layers. Figure 5 is the comparison of measured (circle) and fitted (square) line of forward-biased Schottky characteristics.

4. Conclusion

We discover an obvious recess around 0.5 V of GaN based Ni/Au gate Schottky forward $I-V$ characteristics after thermal storage. The decrease of 2DEG density results in the enhancement of the restricting-current ability of reversed-biased diode in heterojunction which brings on the recess phenomenon. The conventional approach to extract Schottky parameters cannot meet the new demands. We bring forward a revised approach by analyzing the energy band and obtain good fit effects. It is very important to the development of Schottky parameter extraction after thermal storage for GaN HEMT, and it provides an evidence for evaluating the reliability of GaN HEMT.

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