Annealing before gate metal deposition related noise performance in AlGaN/GaN HEMTs*

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Abstract: For a further improvement of the noise performance in AlGaN/GaN HEMTs, reducing the relatively high gate leakage current is a key issue. In this paper, an experiment was carried out to demonstrate that one method during the device fabrication process can lower the noise. Two samples were treated differently after gate recess etching: one sample was annealed before metal deposition and the other sample was left as it is. From a comparison of their I_g–V_g characteristics, a conclusion could be drawn that the annealing can effectively reduce the gate leakage current. The etching plasma-induced damage removal or reduction after annealing is considered to be the main factor responsible for it. Evidence is given to prove that annealing can increase the Schottky barrier height. A noise model was used to verify that the annealing of the gate recess before the metal deposition is really effective to improve the noise performance of AlGaN/GaN HEMTs.

Key words: GaN HEMT; annealing before metal deposition; gate leakage current; noise performance

DOI: 10.1088/1674-4926/30/5/054001 **EEACC:** 2520D

1. Introduction

Significant progress has been made for gallium nitride (GaN) high-electron-mobility transistors (HEMTs), especially for power devices and hybrid/monolithic power amplifiers[1, 2]. In accordance with the impressive power results, AlGaN/GaN HEMTs are also promising candidates for low noise applications due to their low noise, high linearity and extraordinary robustness[3]. GaN HEMTs in LNA MMICs are considered able to eliminate the need for additional RF limiting circuitry, which degrades the noise performance and the dynamic range of the system[4].

In order to fabricate AlGaN/GaN HEMTs with high noise performance, controllable gate recess etching and consecutive high-quality Schottky contact processing are of great importance. As expected, after the gate recess by dry etching, the plasma-induced damage, which may exist as dislocations loops, vacancy complexes, recombination centers, or implanted ions, will degrade the device performance[5] and cause an obvious increase in the Schottky gate leakage current that is the key issue for a further improvement of the GaN HEMT noise performance. In the research, thermal annealing before metal deposition is found to be an effective method to reduce the gate leakage current. Trap-assisted Schottky barrier tunneling, thermal emission, and impact ionization are included in the mechanisms affecting the gate leakage current. The plasma-induced damage removal or reduction after annealing is considered to be the main factor responsible for the decrease of the gate leakage current of AlGaN/GaN HEMTs.

2. Device structure and fabrication

Figure 1 shows the layer structure of the transistor which is an $Al_{0.2}Ga_{0.8}N$/AlN/GaN multilayer grown on a semi-insulating 4H-SiC substrate. The two inch epitaxial wafer grown by MOCVD was provided by the Institute of Semiconductors of the Chinese Academy of Sciences. An averaged electron mobility of 1250 $cm^2/(V\cdot s)$ and a sheet carrier density of 1.4×10^{13} cm^{-2} were obtained from room-temperature Hall measurements. In order to obtain a good noise performance of the GaN HEMTs, a kind of four-finger transistor with air bridges was designed, as shown in Fig. 2. The AlGaN/GaN HEMT fabrication started with the definition of the active device area. This isolation was implemented by an ion implantation mesa. Next, the ohmic contacts were formed by first depositing an ohmic metal stack of Ti/Al/Ti/Au, followed by rapid thermal annealing (RTA) at 870 °C for 50 s. All these steps resulted in a low ohmic contact resistivity of $10^{-6}\Omega\cdot cm^2$. After the SiN film, which was used for passivation, was grown by PECVD, a gate recess was etched by using a fluorine-based followed by a chlorine-based ICP process. Then, the T-Schottky gate was formed by Ni/Au evaporation and a

i-GaN	3 nm
i-AlGaN	25 nm
AlN	1 nm
GaN	3 μm
4H-SiC	

Fig. 1. Layer structure of the transistor grown by MOCVD.

* Project supported by the State Key Development Program for Basic Research of China (No. 2002CB311903) and the Key Program of the Chinese Academy of Sciences (No. KGCX2-SW-107).

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Received 23 November 2008, revised manuscript received 8 January 2009

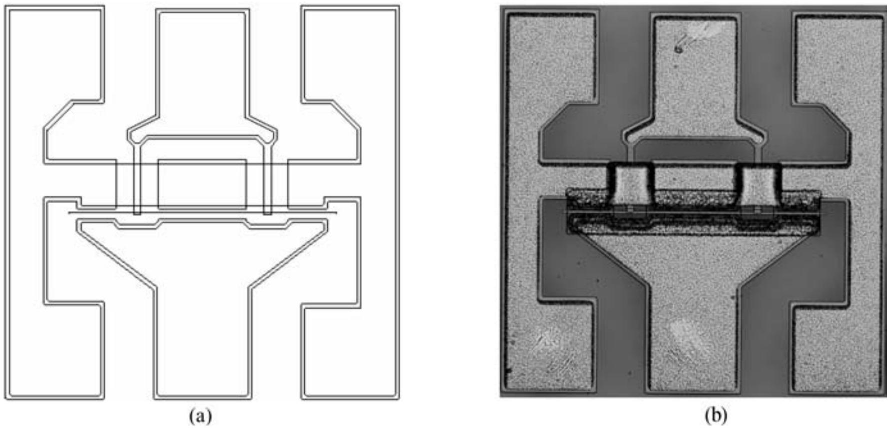

Fig. 2. (a) Layout and (b) top view micrograph of the low-noise GaN HEMT.

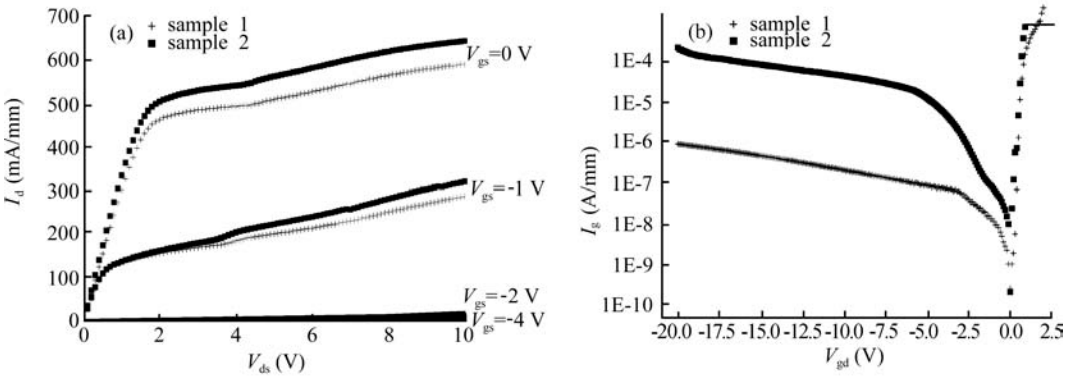

Fig. 3. (a) Comparison of the I_d–V_{ds} characteristics of sample 1 and sample 2, with V_{gs} varied from −4 to 0 V (step width: 1 V); (b) Comparison of the I_g–V_{gd} characteristics of sample 1 and sample 2, with V_{gd} varied from −20 to 2 V.

subsequent lift-off process. The gate length and width were 0.25 μm and 140 (35 × 4) μm, respectively. At last, Au air bridges were deposited by electroplating, in order to connect the different source areas.

3. Experiment and discussions

Before the formal gate recess etching, monitor devices were first etched while measuring the ungated I_{ds} repeatedly throughout the etching process to determine the optimal etching condition. After etching and resist stripping, the wafer was divided into two parts: one sample (sample 1) was annealed under nitrogen (N_2) atmosphere for 2 min at 400 °C and a Schottky metallization (Ni/Au) was deposited through a stencil mask by e-beam evaporation, while the other (sample 2) was not annealed and Ni/Au gates were directly deposited. Except for the annealing, all other process steps are the same for both samples. After electroplating, the measurements of the DC characteristics were performed using an Agilent 4155A semiconductor parameter analyzer on both samples. Figure 3 gives the DC test results.

Figure 3(a) shows the comparison of the typical drain current–voltage characteristics of sample 1 and sample 2, with V_{gs} varying from –4 to 0 V. It can be seen that the devices annealed before metal deposition show a lower maximum drain current of 591 mA/mm at a gate bias of 0 V than the non-annealed devices (645 mA/mm). It was concluded that the annealing process may decrease the polarization induced 2-DEG concentration at the AlGaN /GaN interface; thus, causing the slight decrease in current[6]. Figure 3(b) shows the comparison of the reverse gate current characteristics of the two samples. It can be concluded that the annealing step before the metal deposition is effective for suppressing the gate leakage current. The improvement of the noise performance can be mainly attributed to this suppression, as shown later. Several factors are responsible for the characteristic differences of the samples.

Although gate recess etching by ICP can increase the maximum transconductance and f_t of HEMTs due to the enhancement of the control of the channel by the gate, it will inevitably cause plasma-induced damage to the AlGaN surface. The damage includes defects or dislocations in the lattice, formation of dangling bonds on the surface, implanted etch ions, and recombination centers. Among them, nitrogen vacancy-induced defects near the Schottky interface, which are induced by the escape of N atoms from the surface, are believed to be the main plasma damage[7, 8]. These trapping centers acting as fixed defect charges affect the strain and surface states of the AlGaN layer and increase the electric field at the AlGaN layer beneath the gate electrode, which results in narrowing and reduction of the effective Schottky barrier, as shown in Fig. 4. Thus, the Schottky barrier tunneling of charge carriers will greatly increase after etching. One mechanism for

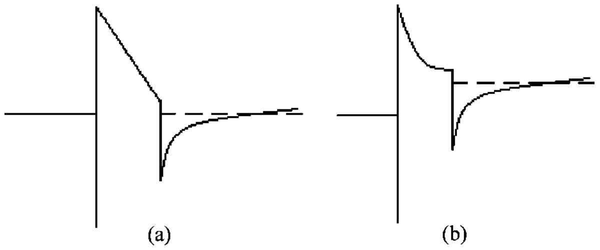

Fig. 4. Comparison of the energy band structure change (a) before and (b) after gate recess etching.

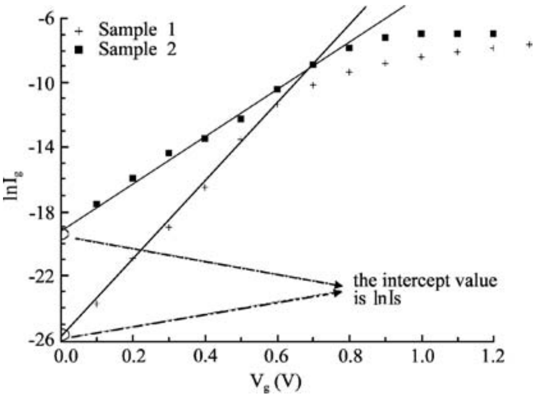

Fig. 5. Plot of ln I_g as a function of V_g derived from the forward-biased I_g–V_g Schottky characteristic of Fig. 3(b).

the gate leakage current is the trap-assisted tunneling through the AlGaN barrier. Sample 1 with the annealing treatment partially recovers or terminates the N vacancy-related defects, leading to a reduction of traps and surface states in the AlGaN layer. Accordingly, its Schottky barrier is higher than that of sample 2. As shown by calculations, the ideality factor of sample 1 is 2.37, which is not very different from 2.09 of sample 2. The formulae and graphs below give evidence of different barrier heights.

I–*V* characteristics of a Schottky barrier are generally described by

$$I = I_S\left(\exp\frac{qV}{nkT} - 1\right), \tag{1}$$

$$I_S = AA^*T^2\exp\left(-\frac{q\phi_b}{kT}\right), \tag{2}$$

where I_S is the saturation current density, A is the contact area, A^* is the effective Richardson constant, ϕ_b is the barrier height, n is the ideality factor, k is the Boltzmann constant, and T is the absolute temperature. Equation (2) shows that if we can get the difference of I_S of the two samples, we can compare their Schottky barrier heights. From Eqs. (1) and (2), we can derive that

$$\ln I \approx \ln I_S + \frac{qV}{nkT}, \tag{3}$$

$$\phi_b = \frac{kT}{q}\ln\frac{AA^*T^2}{I_S}. \tag{4}$$

Equation (3) suggests that a linear fit to the semi-log plot of the *I*–*V* curve at $V = 0$ yields $\ln I_s$, as shown in Fig. 5. As shown,

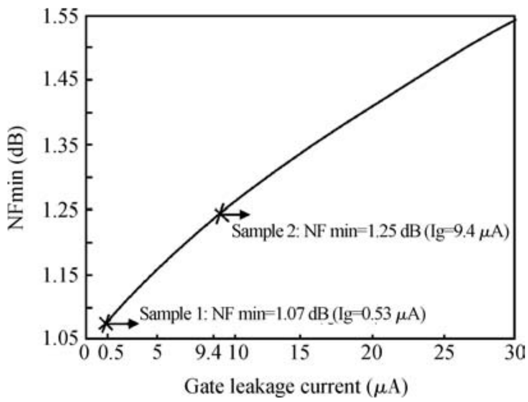

Fig. 6. Simulated minimum noise figure at 8 GHz with different gate leakage currents for GaN HEMTs.

I_S of sample 2 is larger than I_S of sample 1. Considering Eq. (4), it is concluded that thermal annealing before metal deposition can increase the Schottky barrier height of a GaN HEMT, thus effectively suppressing the etching-trap-assisted tunneling with the result that the gate leakage current greatly decreases.

Except for Schottky barrier tunneling, thermal emission[9] of carriers direct from the metal into the conductive dislocations and impact ionization[10] are also responsible for the mechanism of gate leakage current. In one word, the annealing process before the metal deposition can remove or mitigate etching-induced damage and suppress the gate leakage current related to damage, thus, reducing the noise figure of GaN HEMTs.

To explore how the gate leakage affects the noise performance, a modified van der Ziel noise model[11] is employed. The model includes a shot noise source for the gate leakage current, which can be a large contributor to the overall noise figure for an AlGaN/GaN HEMT, as its gate leakage current is higher than that of other material systems. As long as we get the small-signal model parameters from *S*-parameter measurements and the gate leakage current from DC measurements, we can obtain the noise information of the GaN HEMTs. A small-signal parameter extraction was performed using an Agilent 8510C network analyzer and an ICCAP. The small-signal parameters of the two samples were not remarkably different. However, at biases of $V_g = -2$ V and $V_d = 5$ V, which is the optimum condition for low noise, the DC measurement of the gate leakage current of sample 2 yields 9.4 μA, compared with 0.53 μA of sample 1. After the noise model and all the measured/extracted parameters have been implemented into Matlab, the simulated effect of different gate leakage currents on NFmin at 8 GHz (X band) with optimized bias can be clearly seen from Fig. 6. Annealed sample 1 with a gate leakage current of 0.53 μA shows a better noise performance than non-annealed sample 2, having a leakage current of 9.4 μA.

It can be concluded that an annealing treatment of the gate recess before the metal deposition has the potential to improve the noise performance of AlGaN/GaN HEMTs on SiC substrate. Further work is needed to find other mechanisms that affect the noise performance of GaN HEMTs, and corresponding steps should be taken in the device-making processes to further reduce the noise figure.

4. Conclusions

Although the outstanding microwave power performance of AlGaN/GaN HEMTs has been widely reported, the potential of their noise performance has not been fully explored. Gate leakage current is one of the trickiest issues, which limits the microwave noise performance of AlGaN/GaN HEMTs. In this paper, one process method to suppress the gate leakage current is reported. Thermal annealing of the gate recess before metal deposition is found to be an effective method to improve the noise performance of GaN HEMTs. A reasonable explanation is given. The etching plasma-induced damage removal or reduction after annealing is helpful for suppressing the gate leakage current of AlGaN/GaN HEMTs, thus decreasing the noise figure.

Acknowledgment

The authors would like to thank Professor Wang Xiaoliang from the Institute of Semiconductors of the Chinese Academy of Sciences for providing the GaN HEMT epitaxial wafer.

References

[1] Sheppard S T, Smith R P, Pribble W L, et al. High power hybrid and MMIC amplifiers using wide-bandgap semiconductor devices on semi-insulating SiC substrates. Device Research Conference Digest, 2002: 175

[2] Palmour J W, Sheppard S T, Smith R P, et al. Wide bandgap semiconductor devices and MMICs for RF power applications. IEDM Tech Dig, Washington D C, 2001: 385

[3] Parikh P, Wu Y, Moore M, et al. High linearity, robust, AlGaN-GaN HEMTs for LNA and receiver ICs. Lester Eastman Conf Abstract Book, Newark, 2002: 56

[4] Krausse D, Quay R, Kiefer R, et al. Robust GaN HEMT low-noise amplifier MMICs for X-band applications. Proceedings 12th GaAs Symposium, Amsterdam, 2004: 71

[5] Pang S W, Geis M W, Efremow N N, et al. Effects of ion species and adsorbed gas on dry etching induced damage in GaAs. J Vac Sci Technol, 1985, B3: 398

[6] Lin Z, Kim H, Lee J, et al. Thermal stability of Schottky contacts on strained AlGaN/GaN heterostructures. Appl Phys Lett, 2004, 84: 1585

[7] Li Chengzhan, Pang Lei, Liu Xinyu, et al. Effect of plasma dry etching on gate leakage of recessed AlGaN/GaN HEMTs. Chinese Journal of Semiconductors, 2007, 28(11): 1777

[8] Shul R J, Zhang L, Baca A G, et al. High density plasma induced etch damage of GaN. Proc Mater Res Soc Symp, 1999, 573: 161

[9] Jia S, Cai Y, Wang D, et al. Enhancement-mode AlGaN/GaN HEMTs on silicon substrate. IEEE Trans Electron Devices, 2006, 53(6): 1474

[10] Kunihiro K, Kasahara K, Takahashi Y, et al. Experimental evaluation of impact ionization coefficients in GaN. IEEE Electron Device Lett, 1999, 20(12): 608

[11] Sanabria C, Chakraborty A, Xu H, et al. The effect of gate leakage on the noise figure of AlGaN/GaN HEMTs. IEEE Electron Device Lett, 2006, 27(1): 19