Electrical characteristics of AlInN/GaN HEMTs under cryogenic operation*

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Electrical properties of an AlInN/GaN high-electron mobility transistor (HEMT) on a sapphire substrate are investigated in a cryogenic temperature range from 295 K down to 50 K. It is shown that drain saturation current and conductance increase as transistor operation temperature decreases. A self-heating effect is observed over the entire range of temperature under high power consumption. The dependence of channel electron mobility on electron density is investigated in detail. It is found that aside from Coulomb scattering, electrons that have been pushed away from the AlInN/GaN interface into the bulk GaN substrate at a large reverse gate voltage are also responsible for the electron mobility drop with the decrease of electron density.

Keywords: AlInN/GaN heterostructure, high-electron mobility transistor (HEMT), cryogenic temperature, two-dimensional electron gas (2DEG) mobility

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1. Introduction

AlInN/GaN high-electron mobility transistors (HEMTs) have attracted great attention for high-frequency and high-power amplifier application.[1–5] Compared with conventional AlGaN/GaN transistors, AlInN/GaN HEMTs can obtain substantially higher polarization-induced two-dimensional electron gas (2DEG) density.[6] In addition, the growth of lattice-matched AlInN barriers over the GaN channel can eliminate stress and piezopolarization, which potentially improves the stability of the heterostructure and reduces or gets rid of the surface related current collapse.[7–9] With improved material quality and device processing technologies, significant improvements of direct current (DC) and radio frequency (RF) performances of such HEMTs have been achieved. It was reported recently that output power of 10 W/mm at 10 GHz[1] and 230 GHz current gain cutoff frequency[3] has been achieved in an AlInN/GaN HEMT. On the other hand, it is expected that cryogenic operation can further improve the performance of GaN-based HEMTs by reducing self-heating and scattering on 2DEG. Transient pulse analysis on an AlGaN/GaN HEMT at cryogenic temperature was carried out by Lin *et al.*[10] They observed a more severe current-kink effect at cryogenic temperature than at room temperature due to trap related process and impact ionization. More recently, Endoh *et al.*[11] investigated the DC and RF characteristics of AlGaN/GaN HEMTs at cryogenic temperature. They found that the cutoff frequency and the maximum transconductance increase with decreasing temperature in a range of 150–300 K, and increase slightly as temperature is below 100 K. Although some work on cryogenic properties of AlGaN/GaN HEMTs can be found in the literature, few studies involve AlInN/GaN HEMTs. In the present paper, we investigate the cryogenic characteristics of AlInN/GaN HEMTs in detail using DC and pulse measurement. The 2DEG sheet resistance of the AlInN/GaN system, and the DC and pulse characteristics of AlInN/GaN HEMTs are measured at temperatures ranging from room temperature down to 50 K. The temperature-dependent electron mobility in the channel varying with the 2DEG density is obtained from the gate capacitance–voltage (C–V) characteristics and channel conductance values.

2. Experiments

In our experiments, the AlInN/GaN transistor structures were grown on sapphire substrates using MEMOCVD® technique developed by Sensor Electronic Technology Inc.[12] In all samples, indium composition in the AlInN barrier layer was close to 17% to obtain the lattice matched AlInN barrier layer. In Hall measurements, the 2DEG density is 2.45×10^{13} cm^{-2}, and the Hall mobility is 1220 cm^2/V·s at room temperature. Transfer length measurement (TLM) patterns and 2-μm-gate-length HEMT devices with various gate widths were fabricated. The electrical characteristics of the devices were measured in a dark and screening vacuum chamber using a Keithley 2612A source meter. The operation temperature was controlled by a helium-gas closed cycle cryostat.

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3. Results and discussion

The temperature dependence of channel 2DEG sheet resistance ($R_{\rm sheet}$) in AlInN/GaN structure, extracted from transfer length measurements (TLM), is shown in Fig. 1. The $R_{\rm sheet}$ is about 220 Ω per square at room temperature, which is in good agreement with the Hall measurement result. The decrease of $R_{\rm sheet}$ with temperature decreasing is due to the reduction of phonon and alloy scattering.[13] On the other hand, the contact resistance shows little change with temperature, indicating a good ohmic contact.[14]

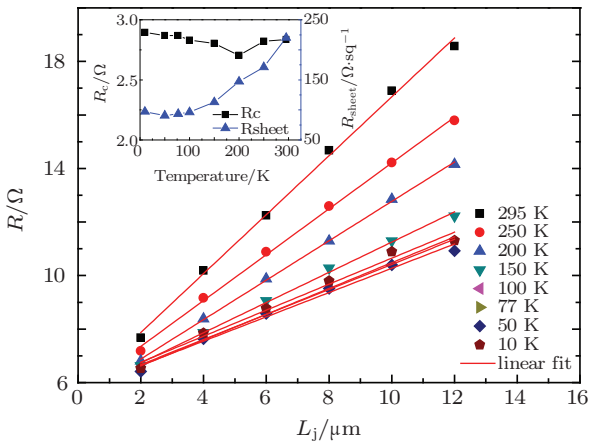


Fig. 1. (color online) Contact and sheet resistance obtained from transfer length measurement. The $L_{\rm j}$ is the gap of TLM pattern.

Figure 2 shows the output characteristics of the transistor with the gate geometry of 2×150 μm^2×2 and source-to-drain distance of 6 μm at four different temperatures. The HEMT is well pinched off at all measured temperatures. The parasitic access resistances reduce as temperature decreases, which appears as the increase of $I_{\rm ds}$ in the linear region in Fig. 2. Meanwhile, the saturation current ($I_{\rm dss}$) rises from 1.13 to 2.06 A/mm as the operating temperature decreases from 295 to 50 K. The increase in $I_{\rm dss}$ ($qnV_{\rm sat}$) can be attributed to the increase of saturation velocity. On the other hand, an obvious self-heating effect is observed over the entire range of temperature. To demonstrate the self-heating effect, the DC and pulse measurements (250-μs pulse width and 1%-duty cycle) are performed. As shown in Fig. 2, at large reverse gate voltages and low drain currents, $I_{\rm ds}$–$V_{\rm ds}$ curves extracted from DC measurements coincide with those from pulse measurements due to small power consumption. Nevertheless, as gate voltage $V_{\rm gs}$ approaches to 0 or is forward biased, pulse measurement gives larger $I_{\rm ds}$ than DC measurement because less heat is generated under the pulse measurement. Although the pulse width used in our measurement is not so short as 200 ns due to the limitation of Keithley 2612A,[14] it still shows some degree of reduction of the self-heating effect. The self-heating effect can be ascribed to the low thermal conductance of the sapphire substrate.[13,15]

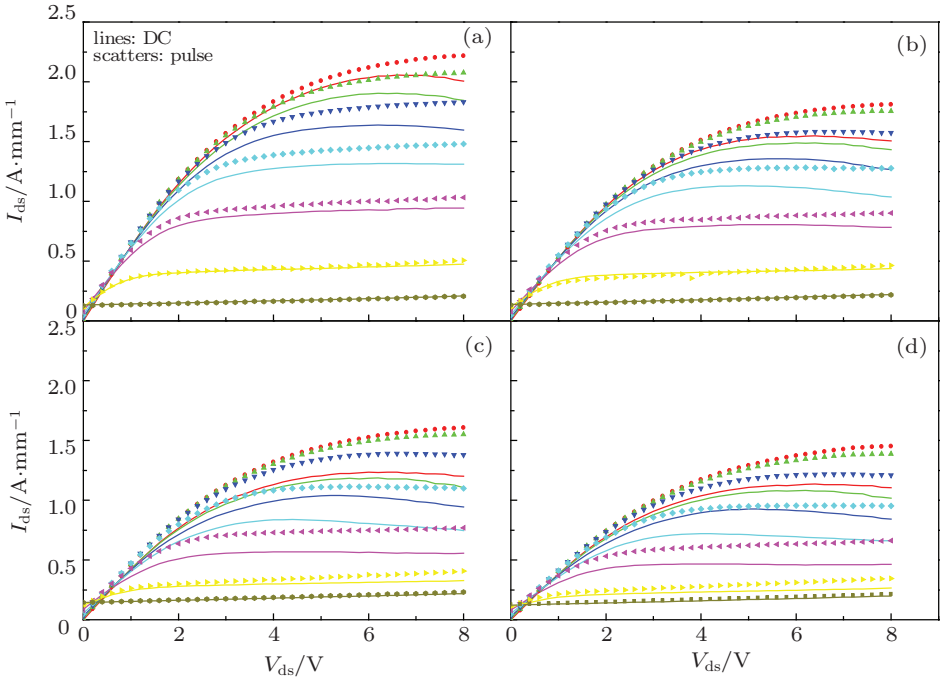


Fig. 2. (color online) Output characteristics of 2-μm-gate AlInN/GaN HEMT at temperatures of (a) 50, (b) 150, (c) 250, and (d) 295 K. Gate bias is from 0 to −12 V with a step of −2 V.

Figure 3 shows transfer characteristics varying with operation temperature. The extracted maximum transconductance at $V_{\rm ds}$ = 1 V decreases from 0.168 to 0.094 S/mm with temperature increasing from 50 to 295 K. As demonstrated by Pozzovivo *et al.*,[16] transconductance strongly depends on the electron mobility in channel ($\mu_{\rm ch}$) for AlInN/GaN and AlGaN/GaN HEMTs. This is consistent with the fact that $\mu_{\rm ch}$ increases with decreasing operation temperature (see Fig. 4).

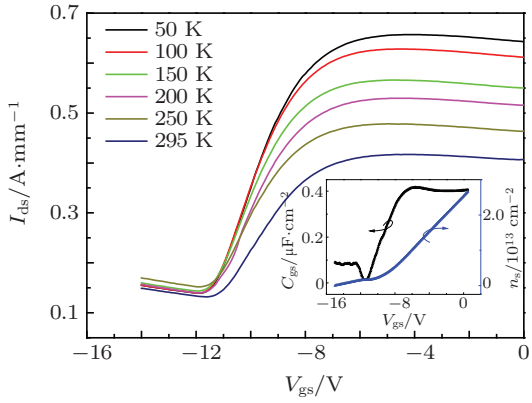


Fig. 3. (color online) Temperature-dependent transfer characteristics of 2-μm-gate AlInN/GaN HEMT at temperatures of 295, 200, 150, 100, and 50 K. In all plots, $V_{ds} = 1$ V. The inset shows the dependences of C_{gs} and 2DEG density on V_{gs}.

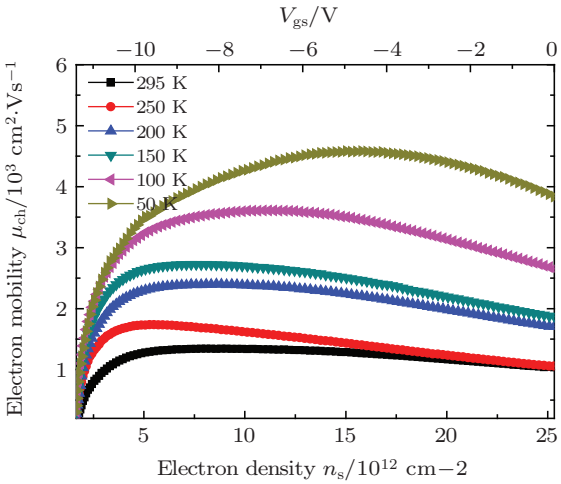


Fig. 4. (color online) Curves of channel electron mobility derived from conductance of AlInN/GaN HEMT's 2DEG density at several different temperatures.

The 2DEG mobility μ_{ch} is extracted from the conductance and the total source-drain resistance $R_{DS}(V_{gs}) = 2R_c + R_{GS} + R_{DG} + 1/G_{ch}(V_{gs})$. Here, n_s is the 2DEG density, W and L_g are the width and length of the transistor, R_c is the source and drain contact resistance, and R_{GS} (R_{DG}) is the series resistance of 2DEG between source and gate (drain and gate).[17] The R_c, R_{GS}, and R_{DG} are calculated from TLM. The $R_{DS}(V_{gs})$ is obtained from transfer characteristics. By integrating gate-source capacitance (C_{gs}) over V_{gs}, we obtain 2DEG density of n_s (see the inset of Fig. 3). Theoretical calculations and experiment results confirm that the 2DEG density in AlInN/GaN heterojunction has little dependence on temperature because of the strong degeneracy.[18] Thus, we use room-temperature 2DEG density n_s to extract the electron mobility. The reduction in μ_{ch} with decreasing value of n_s was usually explained by the Coulomb scattering from ionized impurities, trapped charges, and dislocations in the 2DEG.[17,19] However, the reduction of μ_{ch} at low electron density is partly due to Coulomb scattering. As reverse gate voltage increases, the electron density in the channel is reduced and the electrons are pushed away from the heterojunction interface into the depth of the GaN substrate. The measured electron mobility is converted from the 2DEG mobility to bulk GaN electron mobility at large reverse gate voltage. This deduction is validated by the extracted 2DEG mobility profile along the vertical direction in the AlInN/GaN heterojunction.

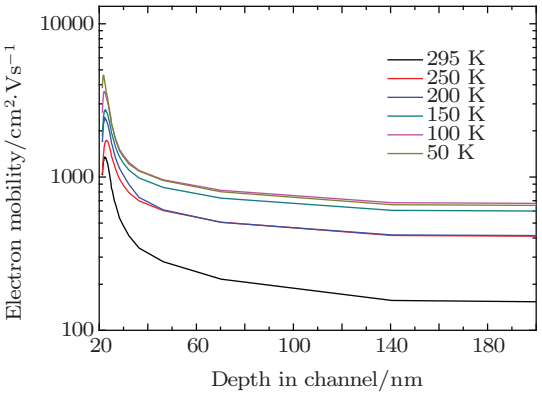


Fig. 5. (color online) 2DEG mobility profiles in channels at several different temperatures.

In Fig. 5, it is clearly shown that μ_{ch} is rapidly converted from 2DEG mobility to GaN bulk electron mobility (100–400 cm^2/Vs at room temperature from Ref. [12]) as electrons are pushed away from the AlInN/GaN interface. On the other hand, μ_{ch} decreases again after it reaches its maximum value. This decrease cannot be explained just by phonon scattering, alloy scattering, and interface roughness, since it is still observed at the low temperature of 50 K, where phonon scattering and alloy scattering should be very weak.[20] Other mechanisms, for example, spillover of electrons from the 2DEG channel to the AlInN barrier layer which brings about parallel low electron mobility parasitic conduction channel, was proposed to explain the mobility reduction at high 2DEG density.[19] However, it may not be taken into account in our case. As shown in Fig. 4, μ_{ch} starts to decrease as the gate is reverse biased. Under such a condition, the parasitic channel is far from being activated, which is supported by the fact that the measured C_{gs} (see the inset of Fig. 3) remains constant as mobility decreases. Therefore, the decrease of mobility at larger 2DEG density should be attributed to intersub-band scattering as electrons begin to occupy the upper sub-bands in the potential well of the AlInN/GaN heterointerface.[21]

4. Conclusion

In this paper, the electrical properties of AlInN/GaN HEMT on the sapphire substrate are evaluated at temperatures ranging from room temperature to 50 K by DC and pulse measurements. As the operating temperature decreases from room temperature to 50 K, the DC saturation current (I_{dss}) rises from

1.13 to 2.06 A/mm, and the maximum transconductance at $V_{ds} = 1$ V rises from 0.094 to 0.168 S/mm. The reduction of channel electron mobility is due to strong Coulomb scattering at low 2DEG density and strong intersub-band scattering at high 2DEG density. A self-heating effect is observed over the entire temperature range due to the low thermal conductance of the sapphire substrate. Thus, high thermal conductance substrates such as SiC or Si are necessary to further improve the performance of AlIn/GaN HEMTs. The dependence of channel electron mobility on electron density is investigated in detail. It is shown that the reduction in μ_{ch} with the decrease in n_s is due to the fact that besides the Coulomb scattering, the electrons that are pushed away from the AlInN/GaN interface into bulk GaN substrate at large reverse gate voltage, are also responsible for the reduction of electron mobility with decreasing electron density.

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