High temperature characteristics of AlGaN/GaN high electron mobility transistors*

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Direct current (DC) and pulsed measurements are performed to determine the degradation mechanisms of AlGaN/GaN high electron mobility transistors (HEMTs) under high temperature. The degradation of the DC characteristics is mainly attributed to the reduction in the density and the mobility of the two-dimensional electron gas (2DEG). The pulsed measurements indicate that the trap assisted tunneling is the dominant gate leakage mechanism in the temperature range of interest. The traps in the barrier layer become active as the temperature increases, which is conducive to the electron tunneling between the gate and the channel. The enhancement of the tunneling results in the weakening of the current collapse effects, as the electrons trapped by the barrier traps can escape more easily at the higher temperature.

Keywords: AlGaN/GaN high electron mobility transistor, high temperature characteristics, traps, current collapse

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1. Introduction

With a wide band gap and excellent thermal and chemical stability, AlGaN/GaN high electron mobility transistors (HEMTs) are inherently attractive for applications in high-temperature electronics.[1,2] However, thermal effects, such as self-heating and ambient temperature variation, are still vital to the application of the AlGaN/GaN HEMTs. For the effect of temperature on the performance of the AlGaN/GaN heterostructure, some relevant studies have been carried out.[3,4] In the present paper, detailed investigations of direct current (DC) and pulsed characteristics are presented for the AlGaN/GaN HEMTs over the temperature range from room temperature (RT) to 200 °C. Such an investigation is important particularly for understanding the mechanism of the device deterioration under an elevated temperature.

2. Devices and experiments

The AlGaN/GaN heterojunction structure studied in this paper was grown by using the metal-organic chemical vapour deposition (MOCVD). The structure is depicted in Fig. 1. A 100 nm AlN nucleation layer was used to initiate the GaN growth on a (0001) sapphire substrate. The thickness of the GaN buffer layer was 1.2 μm with an unintentional n-type doping level of 1×10^{17} cm^{-3}. The $Al_{0.3}Ga_{0.7}N$ (25-nm thick) was grown as the barrier layer. The measured room-temperature Hall mobility and sheet carrier concentration of the structure were 1188 cm$^2\cdot$V$^{-1}\cdot$s^{-1} and 1.2×10^{13} cm^{-2}, respectively.

The device fabrication started with the mesa isolation by using the reactive-ion etching. The etch depth was 200 nm. The Ohmic contact consisting of Ti/Al/Ni/Au (22 nm/140 nm/55 nm/45 nm) was annealed in the nitrogen ambient at 850 °C for 30 s, yielding a typical contact resistance around 1.0 Ω·mm. The Schottky contact was formed by Ni/Au/Ni (45 nm/200 nm/20 nm). The gate length L_g and the gate width W were 0.5 μm and 100 μm, respectively.

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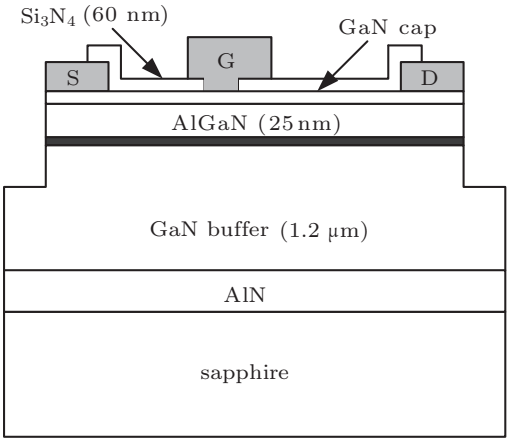


Fig. 1. Schematic cross section of AlGaN/GaN HEMT.

DC and pulsed characteristics of the devices at elevated temperatures (RT, 100 °C and 200 °C) were investigated. The DC characteristics were measured by an Agilent 1500B semiconductor parameter analyzer, while the pulsed characteristics including the capacitance–voltage, the capacitance–frequency, the current collapse and the gate–lag characteristics were measured by using a Keithley 4200 semiconductor parameter analyzer.

3. Results and discussion

Figure 2 shows the measured output characteristics, the transfer characteristics and the parameter shift of the device at RT, 100 °C and 200 °C, respectively. The $V_{\rm G}$, $V_{\rm Gstep}$ and $V_{\rm D}$ in the figure are the gate voltage, the step of the gate voltage and the drain voltage, respectively. As the temperature increases from RT to 200 °C, the saturation drain current $I_{\rm Dsat}$ decreases obviously by 33.4%, the peak trans-conductance $g_{\rm m}$ decreases by 30.5%, while the threshold voltage $V_{\rm TH}$ is shifted slightly toward the positive side.

In order to investigate the DC degradation mechanism of the AlGaN/GaN HEMTs under the high temperature, we combine the test results of the Schottky capacitance–voltage ring and the transmission-line-model (TLM) measurements at different temperatures, thus the variations of channel sheet resistance $R_{\rm sh}$, two-dimensional electron gas (2DEG) density $N_{\rm s}$ and electron mobility μ with temperature can be calculated. The results are shown in Table 1.

From Table 1, we can draw a conclusion that the degradation of the DC characteristics of the device is mainly due to the reduction of the 2DEG mobility and the decrease of the 2DEG density. The observed positive thermal threshold coefficient in Fig. 2 may be attributed to the decrease of the 2DEG density at the higher temperature and thus a lower reverse gate bias is required to deplete the channel.

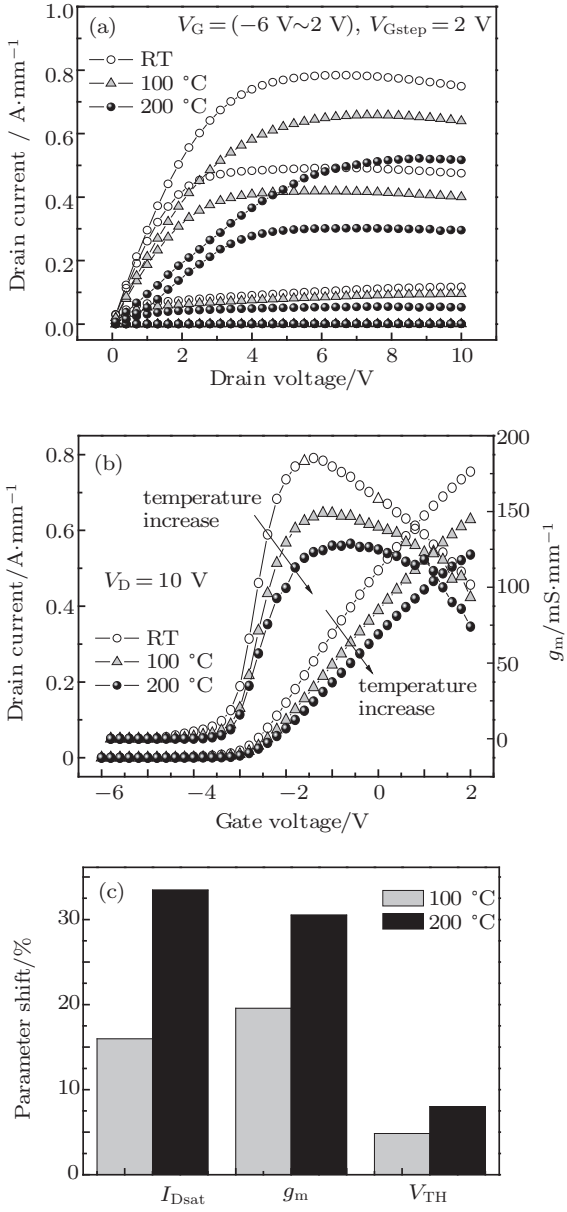


Fig. 2. (a) Output characteristics, (b) transfer characteristics, and (c) parameter shift of the device at RT, 100 °C, and 200 °C.

Table 1. Variations of $R_{\rm sh}$, $N_{\rm s}$, and μ of 2DEG with temperature.

Temperature	$R_{\rm sh}/\Omega\cdot\square^{-1}$	$N_{\rm s}/10^{13}$ cm^{-2}	μ/cm^2·V^{-1}·s^{-1}
RT	442	1.19	1188
100 °C	688	1.07	849
200 °C	1058	1.02	579

Figure 3 shows the variation of the gate leakage current I_G of the AlGaN/GaN HEMTs with the gate voltage at RT, 100 °C, and 200 °C. The V_S in the figure is the source voltage. It can be seen that the gate leakage current increases as the temperature rises, which would become a serious problem in the high temperature application of the devices.[5] In addition, the insert of Fig. 3 shows that the gate leakage current at $V_{gs} = -20$ V meets the exponential growth relationship with the increasing temperature.

The Schottky barrier height Φ_b and the ideality factor n under different temperatures are extracted to analyze the reason for the increase of the gate leakage current. The results are listed in Table 2. As the temperature increases, there appear a lower barrier height and a higher ideality factor. This is probably due to the fact that some gate leakage mechanisms other than the thermionic emission mechanism become dominant as the temperature rises.

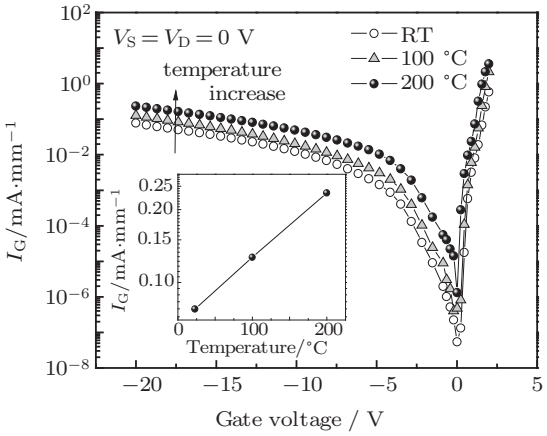


Fig. 3. Variation of gate leakage current of AlGaN/GaN HEMTs with gate voltage at three different temperatures, showing that the gate leakage current increases with the increasing temperature. The insert shows I_G at $V_{gs} = -20$ V.

Table 2. Values of Φ_b and n of AlGaN/GaN HEMTs at RT, 100 °C and 200 °C.

Device number	RT		100 °C		200 °C	
	Φ_b	n	Φ_b	n	Φ_b	n
1	0.8210	1.7821	0.7447	2.0534	0.5676	3.2534
2	0.7483	2.0134	0.6894	2.1170	0.5101	4.1327
3	0.8390	1.7192	0.7093	2.4506	0.5920	3.3936

Two different mechanisms have been proposed to explain the observed leakage current. The first one is the direct tunneling (DT) from the metal into the semiconductor, which is dominant at lower temperatures. The second one is the trap-assisted tunneling (TAT), which has the exponential temperature dependence and becomes significant at higher temperatures.[6] Since the DT current is well below the TAT one in the temperature range of interest[7] and the measured gate leakage current is consistent with the exponential temperature dependence of the second mechanism, the TAT is considered to be the dominant I_G mechanism for the temperature range from RT to 200 °C. Apart from the agreement of the measured I_G data with the TAT model, there is an independent evidence for the presence of such traps in the literature.[8] The scanning capacitance microscopy has shown the presence of threading dislocations in the AlGaN layer. The discussion above indicates that the temperature primarily affect the gate current by increasing the activity of the traps in the AlGaN barrier, which facilitates the TAT.

The current collapse characteristics of the AlGaN/GaN HEMTs are measured with a Keithley 4200 semiconductor parameter analyzer at RT, 100 °C and 200 °C. The results are shown in Fig. 4. First, the DC I–V characteristics are measured, from which the un-collapsed I_{Dsat} is extracted. Following the above measurement, the collapsed I_{Dsat} is extracted by measuring the pulsed I–V characteristics under the bias condition of $V_{GQ} = -10$ V and $V_{DQ} = 0$ V, where V_{GQ} and V_{DQ} are the Q points of the gate voltage and the drain voltage set in the dual-pulse measurement. The pulse width is 0.5 μs and the pulse separation is 1 ms. The ratio between I_{Dsat} values obtained under those two different conditions is used as a figure of merit to quantify the current collapse. As shown in Fig. 4, the current collapse in the device is weakened at the higher temperature, for which there are two reasons. 1) The activity of the traps in the AlGaN barrier is increased, and 2) the electrons obtain higher energy, as the temperature rises. Both reasons make it easier for electrons to escape from traps into the barrier layer. Thus, the depletion effect of the trapped electrons in

the channel is suppressed, eventually leading to the weakening of the current collapse. This can be further verified by conductance measurements that will be shown in this paper.

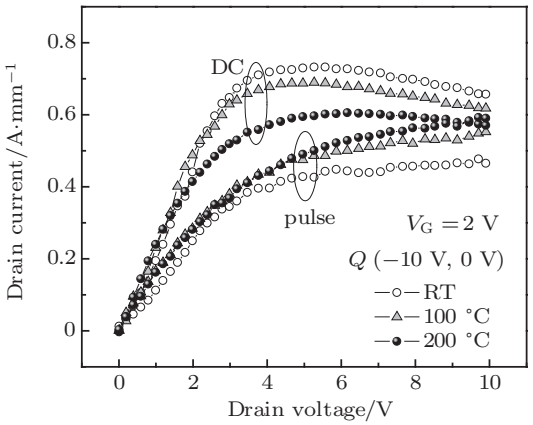


Fig. 4. Drain currents of AlGaN/GaN HEMTs versus drain voltage at RT, 100 °C and 200 °C.

The conductance measurements in the frequency range from 10 kHz to 10 MHz are used to characterize the trapping effects in the devices prepared. The conductance G_P as a function of frequency under the assumption of a continuum of trap levels can be expressed as[9]

$$\frac{G_P}{\omega} = \frac{qD_T}{2\omega\tau_T} \ln[1 + (\omega\tau_T)^2],$$

where D_T is the trap density, τ_T is the trap state time constant and ω is the radial frequency. Trap concentration D_T and trap state time constant τ_T can be extracted by fitting the experimental $G_P(\omega)$ data. Typical curves of G_P/ω versus ω from RT to 200 °C for the devices measured at a gate bias of −2.6 V are shown in Fig. 5.

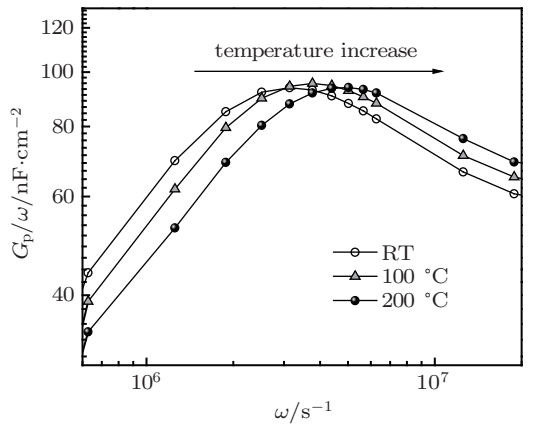


Fig. 5. Conductance as a function of frequency for the CV structure at RT, 100 °C and 200 °C.

A positive shift of curve without any significant change in the peak value is observed as the temperature increases. The values of D_T and τ_T under different temperatures are obtained by the experimental data fitting, through which we can obtain the information that the time constant of the dominant trap decreases from 0.32 μs to 0.2 μs and the concentration does not change significantly as the temperature rises. This shows that with the increasing temperature, no new trap is generated in the AlGaN/GaN HEMTs, while the activity of the original trap is enhanced.

The gate–lag characteristics of the prepared device measured under the bias condition of V_{GQ} = −10 V and V_D = 10 V with the increasing temperature are shown in Fig. 6. The pulse width of the gate terminal is 100 μs and the pulse separation is 1 ms. As shown in Fig. 6, a kind of jitter phenomenon is observed during the transition process of the gate from off to open. This is probably due to the gradual release of the electrons captured previously by the traps in the device.

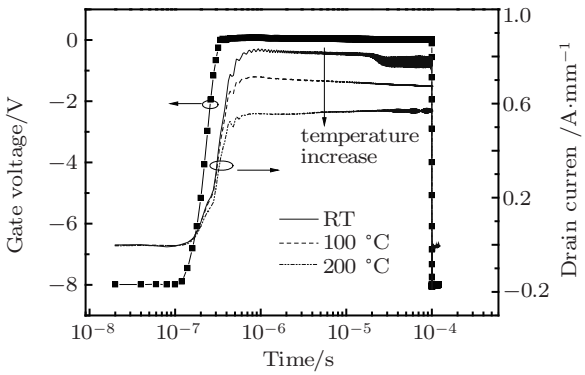


Fig. 6. Gate–lag characteristics of AlGaN/GaN HEMTs at RT, 100 °C and 200 °C.

No significant change is observed during the rising phase of the gate–lag characteristics, indicating that there is no surface trap generation in the heating stage. Therefore, it is reasonable to postulate that the variations of the gate leakage current and the current collapse at higher temperatures would most likely be associated with the traps in the AlGaN barrier layer.

4. Conclusion

DC and pulsed degradation characteristics for AlGaN/GaN HEMTs on sapphire are studied under high temperature and the possible mechanism for the change of the device performance is presented in this paper.

The saturation drain current and the peak transconductance decrease with the increasing temperature, which is mainly due to the reduction in the 2DEG mobility and the decrease in the 2DEG density. A reduction in the barrier height and an increase in the ideality factor are observed in the Schottky characteristics during the warming process, indicating that the TAT mechanism is gradually dominant as the temperature rises. The temperature affects the gate leakage current by increasing the activity of the traps in the AlGaN barrier, which facilitates the TAT.

Our study on the conductance–frequency and the gate–lag characteristics reveals that no new trap is generated in the AlGaN/GaN HEMT, while the activity of the original trap in the AlGaN barrier is enhanced as the temperature increases, which contributes to the electron escaping from the traps in the barrier layer, thus suppresses the depletion effect of the trapped electrons in the channel and eventually leads to the weakening of the current collapse.

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