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COMMUNICATIONS

PERFORMANCE OF AlGaN/GaN HETEROSTRUCTURE FIELD–EFFECT TRANSISTORS AT HIGHER AMBIENT TEMPERATURES

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The paper deals with performance evaluation of the AlGaN/GaN heterostructure field-effect transistors (HFETs) at higher ambient temperatures, between 25 °C and 425 °C. The output and transfer characteristics are continuously degraded with increased temperature. It is found that the saturation drain current, the series resistance and the peak transconductance of devices investigated decrease nearly identically with decreased temperature, if their values are normalized to the particular room temperature values. The decrease from 25 °C to 425 °C is about 70%. From this result one can conclude that the performance of AlGaN/GaN HFETs investigated at higher ambient temperatures depends on the total drain- source conductance, which includes the channel conductance and the source and drain ohmic contact resistances.

Keywords: AlGaN/GaN heterostructure field-effect transistors, high ambient temperatures

1 INTRODUCTION

The wide band-gap of GaN is the basic argument for the use of GaN-based devices at high ambient temperatures. Investigations of high temperature operation of AlGaN/GaN heterostructure field-effect transistors (HFETs) have started already more than ten years ago [1], but still a large number of papers dealing with theoretical (simulations) and experimental analysis of this topic are presented [Refs. 2–10 and references therein]. Since recently, also the application of AlGaN/GaN Hall effect sensors at high temperature magnetic field measurement and mapping has been reported [11–13]. A conductance decrease in the two-dimensional electron gas (2DEG) with increased temperature is observed in all these studies. As a result of this decrease of the drain current and transconductance of an AlGaN/GaN HFET at higher temperatures is observed. Mostly a combined effect of carrier mobility and saturation velocity, which both decrease with increased temperature, is considered to describe the temperature dependent behaviour of these devices [1, 3, 6]. However, also explanation that only the carrier velocity in the 2DEG is responsible for temperature dependent device performance was published [2]. Moreover, very different degradation of the saturation drain current $I_{DS,s}$ and peak transconductance g_m with increased temperature is observed by various authors, *eg* only 30 % decrease [2] as well as 6070 % decrease [1, 3, 7] of the $I_{DS,s}$ and g_m at 300 °C compared to the room temperature values. Finally, similar temperature dependent performances were found for HFETs on sapphire and SiC substrates [3], but different one for HFETs on sapphire and Si substrates [4]. All these indicate that the properties of AlGaN/GaN HFETs at higher ambient temperature need to be studied in more details.

In this paper, the properties of AlGaN/GaN HFETs at the ambient temperature, which was varied between the room temperature and 425 °C, are described and evaluated. It is shown that the saturation drain current, peak transconductance and series resistance of the devices investigated decrease similarly with increased temperature with respect to their room temperature values. Their temperature decrease indicates that only the carrier mobility in the 2DEG channel is responsible for the observed behaviour.

2 EXPERIMENT

The AlGaN/GaN material structure for devices reported here consisted of 1 μm undoped GaN and a 28 nm undoped $Al_{0.25}Ga_{0.75}N$ layers grown on sapphire substrates by metal-organic chemical vapor deposition (MOCVD). Hall effect characterization of the material structure using van der Pauw samples yielded a sheet carrier density $n_s = 7 \times 10^{12}\text{cm}^{-2}$ and electron mobility $\mu_n = 750\,\text{cm}^2/\text{Vs}$, both measured at room temperature. Device fabrication consisted of conventional FET fabrication steps. At first, a mesa-etching isolation using argon sputter etching was performed. After that, ohmic contacts were prepared by evaporating multilayered Ti/Al/Ni/Au sequence followed by a rapid thermal annealing at 850 °C

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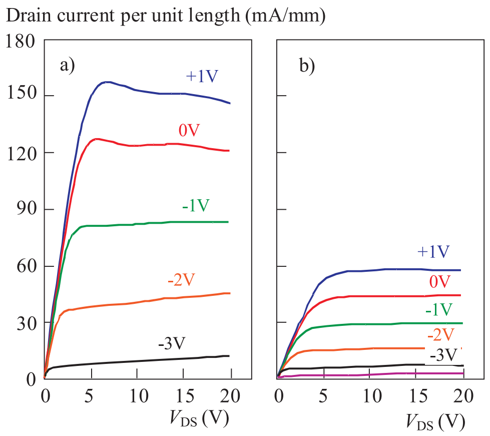

Fig. 1. Typical I–V characteristics measured on AlGaN/GaN HFETs at room temperature (a) and 350 °C (b) The gate voltage was changed from $+1$ V to -4 V, in increment of -1 V.

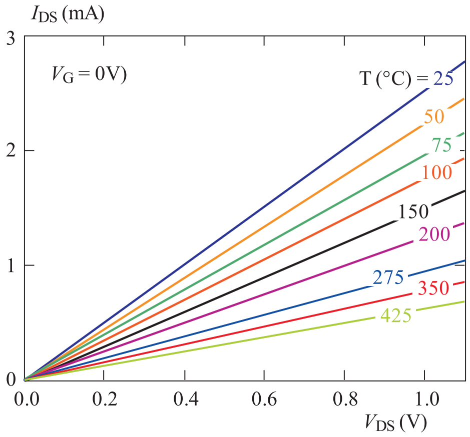

Fig. 2. I–V characteristics of AlGaN/GaN HFET in their linear region ($V_G = 0$ V) at various ambient temperatures. An increase of the series resistance is demonstrated.

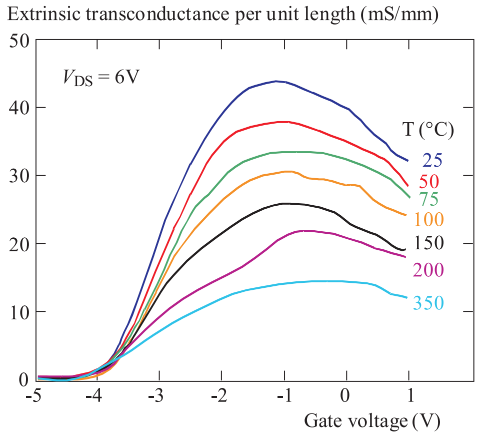

Fig. 3. Transconductance characteristics of AlGaN/GaN HFET for various ambient temperatures measured at the drain-source voltage of 6 V.

for 30 s in a N_2 ambient. The Schottky gate metallization consisted of a Ni/Au double-layer. Devices with a gate length of 2 and 4 μm and a gate width of 70 μm (one finger) were prepared.

The temperature dependent measurements of the AlGaN/GaN HFETs performance were done using a laboratory thermal chamber LHT6/30 from Carbolite, UK. The ambient temperature was changed step-by-step from the room temperature up to 425 °C and hold constant (temperature stability ±1.5 °C) during the measurement of static output and transfer characteristics.

3 RESULTS AND DISCUSSION

The static I–V characteristics of AlGaN/GaN HFETs measured at room temperature yielded a saturation drain current $I_{DS,s}$ of ~ 160 mA/mm at $V_G = 1$ V and good pinch-off at -4 V (Fig. 1a). The drain current decreased significantly as the ambient temperature increased. Typical I–V characteristics measured at 350 °C are shown in Fig. 1 too. The temperature decrease of the saturation drain current at 350 °C ($V_G = 1$ V) is about 66 % with respect to its room temperature value. This is much more than up to 300 °C reported decrease of only 30 % by Simin *et al* [2], but in agreement with 60–70 % decrease published in [3, 7]. An increase of the drain leakage current at pinch-off state can be observed at 350 °C, which might indicate on a parallel conduction through GaN buffer at higher temperatures. The threshold voltage, evaluated from an $I_{DS}^{1/2}$ vs V_G plot (not shown here), does not change with the temperature. This is in agreement with the fact that according literature the carrier density should be nearly constant in the temperature range of our interest. This also indicates that an eventual thermal activation of traps does not occur in our devices, as the threshold voltage $V_{th} \cong -q(N_d - N_t)$.

A slight shift of the knee voltage to higher value, *eg* from ~ 6.5 V at 25 °C to ~ 7.7 V and 350 °C, can be observed from the I-V characteristics at various temperatures (Fig. 1). This is a result of the increased resistance along the un-gated source-drain region with increased ambient temperature. Figure 2 shows the un-gated I-V characteristics in the linear region ($V_{DS} \leq 1.1$ V) for various ambient temperatures between 25 °C and 425 °C. It is clear that the series resistance increases continuously and significantly with increased temperature. We note here that the decrease of the series conductance $1/R_s$ from the room temperature to 350 °C is about 69 %, *ie* similar as for $I_{DS,s}$. Details concerning temperature dependence of the series conductance are given below.

Temperature dependent transconductance measurements yielded similar results as those of the drain current and series conductance. Figure 3 shows typical characteristics of the extrinsic transconductance of the AlGaN/GaN HFET for various ambient temperatures ($V_{DS} = 6$ V). The transconductance decreased strongly with increased various ambient temperatures ($V_{DS} = 6$ V). The transconductance decreased strongly with increased temperature and the 350 °C peak value is about 68 % of that at the room temperature.

In the next, we evaluated the temperature dependence of measured saturation drain current at various gate volt-

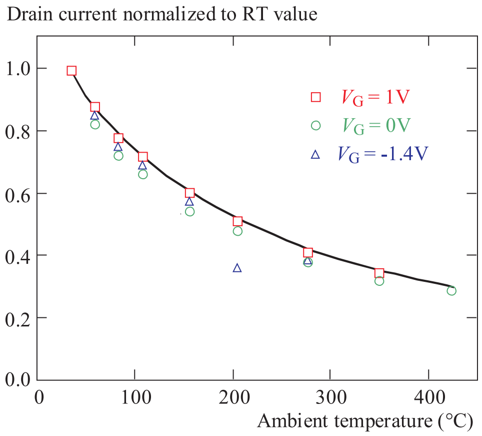

Fig. 4. Saturation drain current normalized to its room temperature value for AlGaN/GaN HFET at various ambient temperatures ($V_G = 1$ V, 0 V and -1.4 V).

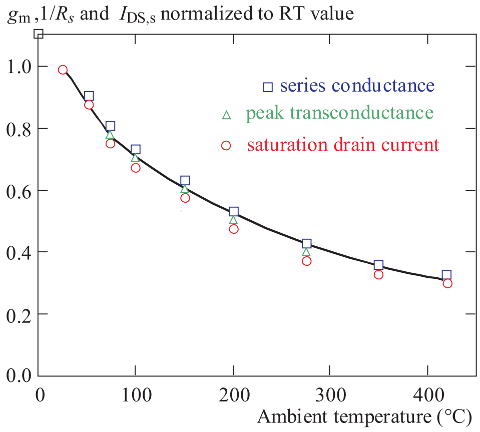

Fig. 5. Peak transconductance g_m and series conductance $1/R_s$ normalized to their room temperature values for AlGaN/GaN HFET at various ambient temperatures. Saturation drain current $I_{DS,s}$ at $V_G = 0$ V, replotted from Fig. 4., is shown for comparison.

ages. We used the gate voltage of 1 V (common value for comparing the drain currents of D-mode GaN-based HFETs), 0 V (un-gated case) and -1.4 V (gate voltage at which the transconductance exhibit maximum). The saturation drain current was normalized to its room temperature value in all cases and the data obtained are shown in Fig. 4. Exactly the same dependence of the saturation drain current on ambient temperature was obtained for all three values of the gate voltage. This indicates that the drain current does not depend on eventual leakage currents through the AlGaN barrier or GaN buffer. Further, we compared the temperature dependence of the peak transconducance and series conductance. Figure 5 shows the peak transconductance g_m (evaluated from Fig. 3 for $V_G = -1$ V) and the series conductance $1/R_s$ (evaluated from Fig. 2 as derivative value for $V_{DS} \to 0$ V), both normalized to their room temperature values, as a function of ambient temperature of the AlGaN/GaN HFET. The change of the saturation drain current $I_{DS,s}$ at $V_G = 0$ V with the temperature (replotted from Fig. 4.) is shown only for comparison. Again, as for $I_{DS,s}$ at various gate voltages, the same relative temperature dependence of g_m and $1/R_s$ is obtained. From this result one can conclude that the performance of AlGaN/GaN HFETs investigated at higher ambient temperatures depends on the total drain-source conductance, which includes the 2DEG channel conductance and the source and drain ohmic contact resistances. From the recent studies dealing with transport properties of AlGaN/GaN heterostructures at higher temperatures it follows that the sheet carrier density n_s is nearly constant in the range between room temperature and 500 °C. In fact, mostly a slight increase [14, 15] but also a decrease [15, 16] of n_s with increased temperature was reported. However, in both cases the n_s change is too small to influence significantly the channel conductance. On the other hand, the carrier mobility in the AlGaN/GaN 2DEG channel decreases even faster with increased temperature according these works than here evaluated temperature decrease of the saturation current, peak transconductance and series conductance. This indicates, that the transport properties of used heterostructure and performance of prepared AlGaN/GaN HFET devices need to be analyzed simultaneously.

4 CONCLUSIONS

The output and transfer characteristics of the AlGaN/GaN HFETs at higher ambient temperature, between 25 °C to 425 °C, were investigated. The device performance continuously degraded with increased temperature. It is found that the saturation drain current, the series resistance and the peak transconductance, normalized to their room temperature values, decreased nearly identically with increased temperature. At 425 °C they are only 30 % of those measured at 25 °C. The same temperature dependence of $I_{DS,s}$, R_s and g_m indicates that the performance of devices investigated at higher ambient temperatures depends on the total drain-source conductance, which includes the channel conductance and the source and drain ohmic contact resistances.

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