

# Superior DC and RF Performance of AlGa<sub>N</sub>-Channel HEMT at High Temperatures

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**SUMMARY** This paper describes high-temperature electron transport properties of AlGa<sub>N</sub>-channel HEMT fabricated on a free-standing AlN substrate, estimated at temperatures between 25 and 300°C. The AlGa<sub>N</sub>-channel HEMT exhibited significantly reduced temperature dependence in DC and RF device characteristics, as compared to those for the conventional AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT, resulting in larger values in both saturated drain current and current gain cutoff frequency at 300°C. Delay time analyses suggested that the temperature dependence of the AlGa<sub>N</sub>-channel HEMT was primarily dominated by the effective electron velocity in the AlGa<sub>N</sub> channel. These results indicate that an AlGa<sub>N</sub>-channel HEMT fabricated on an AlN substrate is promising for high-performance device applications at high temperatures.

**key words:** AlGa<sub>N</sub> channel, high temperature, HEMT

## 1. Introduction

GaN-based HEMTs are expected as promising devices for high-voltage, high-frequency and high-temperature electronic applications. With an ability to exhibit extremely reduced intrinsic carrier concentration, DC characteristics of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs at elevated temperatures have been reported by many authors [1]–[7]. Kordos et al. reported that with increasing the device temperature to more than 200°C, the saturated drain current of a 2 μm gate-length AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT decreased to below one half of that measured at room temperature [6]. It is evident that the temperature dependence in the DC characteristics of GaN-based HEMTs should be further improved to ensure stable device operation at high temperatures.

Recently, a novel nitride-based HEMT structure, in which AlGa<sub>N</sub> is used as a channel layer, has been proposed [8]–[13]. Nanjo et al. demonstrated that a drain breakdown voltage as high as 1650 V was achieved for an AlGa<sub>N</sub>-channel HEMT with an Al composition of 38% [9]. Tokuda et al. reported that the degradation in the drain current by increasing the device temperature from room temperature (RT) to 300°C was significantly suppressed within 20% by using an AlGa<sub>N</sub> channel with an Al composition of 51% [11]. However, the magnitude of the drain current at 300°C

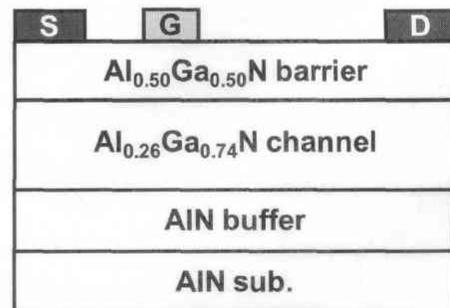
was still larger for the conventional AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT than that for the AlGa<sub>N</sub>-channel device, and no data have been reported on the high-temperature RF performance for the AlGa<sub>N</sub>-channel HEMT.

In this paper, DC and RF performance of AlGa<sub>N</sub>-channel HEMTs fabricated on an AlN substrate is presented. The maximum drain current and the current gain cutoff frequency measured at temperatures from RT to 300°C are compared between devices with an AlGa<sub>N</sub> channel and a Ga<sub>N</sub> channel. The mechanism responsible for the superior performance for the developed AlGa<sub>N</sub>-channel HEMT at high temperatures is discussed.

## 2. Device Fabrication

Figure 1 shows the schematic diagram of an AlGa<sub>N</sub>-channel HEMT fabricated on a free standing C-plane AlN substrate. Epitaxial layers were grown by metal-organic vapor phase epitaxy (MOVPE). The structure consists of a 200-nm-thick AlN buffer, an undoped 600 nm AlGa<sub>N</sub> channel layer with an Al composition of 0.26, and an undoped 27 nm AlGa<sub>N</sub> barrier layer with an Al composition of 0.50. Device fabrication began with mesa isolation using ICP-RIE based on BCl<sub>3</sub> plasma. Then, the source and drain ohmic contacts were formed using a Zr/Al/Mo/Au metal stack annealed at 950°C for 30 s [14]. The specific ohmic contact resistivity and the sheet resistance, estimated by transmission-line-model (TLM) measurements were  $5.0 \times 10^{-4} \Omega \text{cm}^2$  and 4550 Ω/sq, respectively. Ni/Au was used as Schottky gate metallization.

DC characteristics were measured using on-wafer DC probes for a device with a gate length ( $L_g$ ) of 6 μm and a gate



**Fig. 1** Schematic cross section of Al<sub>0.50</sub>Ga<sub>0.50</sub>N/Al<sub>0.26</sub>Ga<sub>0.74</sub>N HEMT on AlN substrate.

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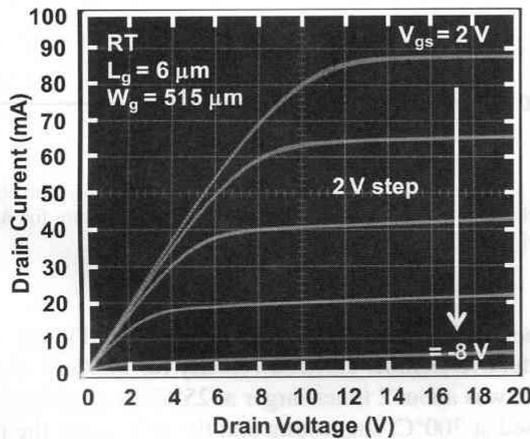
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width ( $W_g$ ) of  $515 \mu\text{m}$ . S-parameter measurements were performed using on-wafer RF probes from 10 MHz to 4 GHz for a device with  $L_g=2 \mu\text{m}$  and  $W_g = 2 \times 50 \mu\text{m}$ . A standard AlGaIn/GaN HEMT with identical electrode dimension was fabricated on a Si substrate. The thickness and Al composition for the AlGaIn barrier layer were 25 nm and 0.25, respectively. Since the main purpose of this work is to study the importance of channel materials, no surface passivation films were used for all the devices.

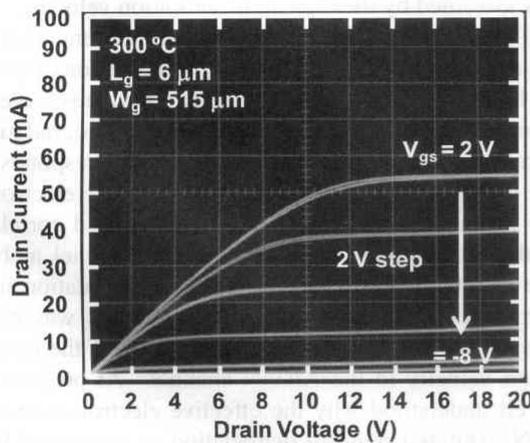
**3. Results and Discussion**

Figures 2(a) and (b) show DC drain I-V characteristics for the fabricated AlGaIn-channel HEMT ( $L_g=6 \mu\text{m}$  and  $W_g=515 \mu\text{m}$ ) measured at  $25^\circ\text{C}$  and at  $300^\circ\text{C}$ , respectively. The maximum drain current defined at a gate-to-source bias voltage ( $V_{gs}$ ) of 2 V was 175 mA/mm at  $25^\circ\text{C}$  and was 106 mA/mm at  $300^\circ\text{C}$ .

Figure 3 shows the maximum drain current as a function



(a)



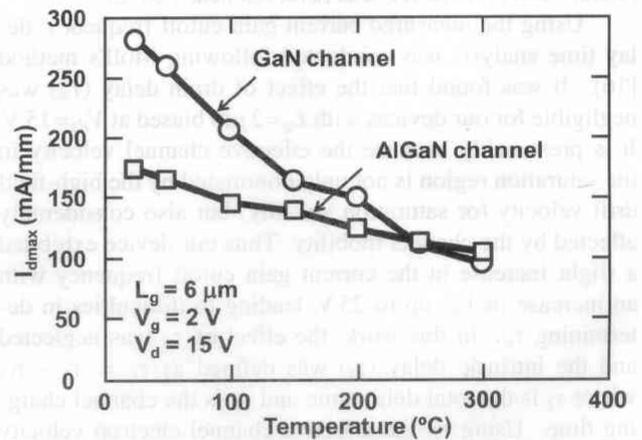
(b)

**Fig. 2** Drain I-V characteristics for AlGaIn-channel HEMT with  $L_g = 6 \mu\text{m}$  and  $W_g = 515 \mu\text{m}$  at (a) RT and (b)  $300^\circ\text{C}$ .

tion of temperature for the AlGaIn-channel HEMT and for the conventional AlGaIn/GaN HEMT. The maximum drain current for the GaIn-channel HEMT decreased from 281 mA/mm at  $25^\circ\text{C}$  to 97 mA/mm at  $300^\circ\text{C}$ , corresponding to about 65% degradation. Similar degradation trend has been observed for AlGaIn/GaN HEMT fabricated on a sapphire substrate, suggesting that the substrate thermal conductivity has minor influence on the comparison of drain current at high temperatures. On the other hand, the degradation for the AlGaIn-channel device was only 40%. Therefore, although the maximum drain current at RT was smaller for the AlGaIn channel, its magnitude was reversed with each other at around  $250^\circ\text{C}$ . At  $300^\circ\text{C}$ , the maximum drain current for the AlGaIn-channel HEMT was about 10% larger than that for the GaIn-channel HEMT. This is the first report demonstrating that an AlGaIn-channel HEMT, having identical device dimension, shows better DC characteristics than AlGaIn/GaN HEMTs when estimated at high temperatures.

In order to investigate the mechanism for the reversal in drain current observed between GaIn and AlGaIn channels, temperature dependent Hall-effect measurements have been performed using the van der Pauw method. Figure 4 shows the Hall mobility measured from RT to  $300^\circ\text{C}$  for heterostructures with an AlGaIn channel and with a conventional GaIn channel. It was found that the channel mobility decreased monotonically with the increase in temperature for both channel materials, indicating that no reversal in the magnitude of channel mobility occurred between the samples at temperatures up to  $300^\circ\text{C}$ .

Figure 5 shows temperature dependence of the current gain cutoff frequency for AlGaIn-channel and GaIn-channel HEMTs ( $L_g=2 \mu\text{m}$  and  $W_g=100 \mu\text{m}$ ) estimated by on-wafer S-parameter measurements. Devices were biased at  $V_{gs}=0 \text{ V}$  and at a drain-to-source voltage ( $V_{ds}$ ) of 25 V. The current gain cutoff frequency was estimated by extrapolating current gain ( $h_{21}$ ) using  $-20 \text{ dB/dec}$  roll-off. S-parameters at each frequency were used after de-embedding parasitic pad capacitance and inductance [15]. The current gain cutoff frequency monotonically decreased with increasing tempera-



**Fig. 3** Maximum drain current ( $I_{dmax}$ ) as a function of temperature for AlGaIn-channel HEMT and for GaIn-channel HEMT.

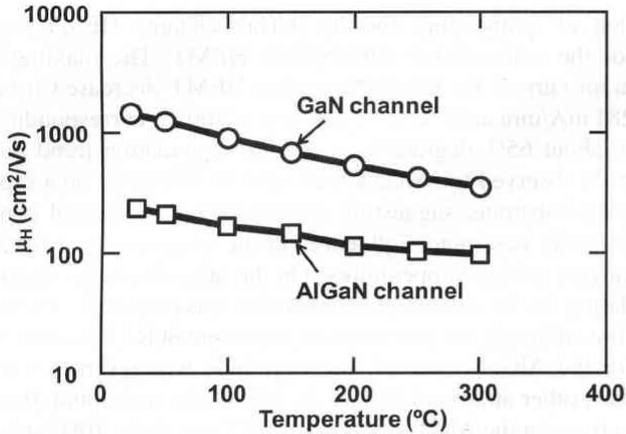


Fig. 4 Temperature dependence of Hall mobility for devices with AlGaIn channel and GaN channel.

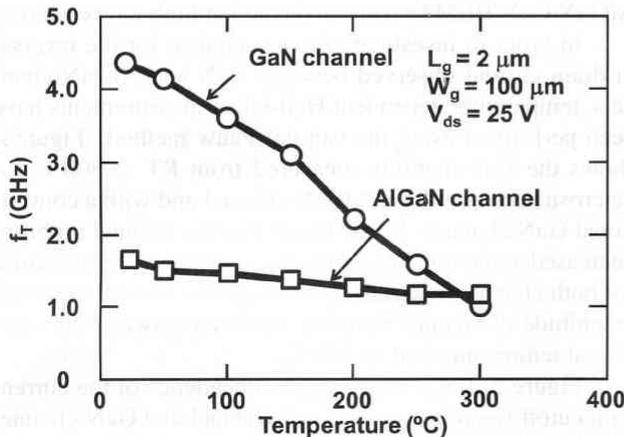


Fig. 5 Current gain cutoff frequency ( $f_T$ ) as a function of temperature for AlGaIn-channel HEMT and for GaN-channel HEMT with  $L_g=2\mu\text{m}$  and  $W_g=100\mu\text{m}$ .

ture in both devices. However, it is obvious that the decrease ratio for the AlGaIn-channel HEMT is extremely smaller than that for the GaN-channel HEMT. More interestingly, the magnitude of the current gain cutoff frequency for the AlGaIn-channel HEMT was reversed near  $300^\circ\text{C}$ .

Using the measured current gain cutoff frequency, delay time analysis was conducted following Moll's method [16]. It was found that the effect of drain delay ( $\tau_d$ ) was negligible for our devices with  $L_g=2\mu\text{m}$  biased at  $V_{ds}=15\text{V}$ . It is presumably because the effective channel velocity in the saturation region is not only dominated by the high-field drift velocity (or saturation velocity) but also considerably affected by the channel mobility. Thus our device exhibited a slight increase in the current gain cutoff frequency with an increase in  $V_{ds}$  up to 25 V, leading to difficulties in determining  $\tau_d$ . In this work, the effect of  $\tau_d$  was neglected and the intrinsic delay ( $\tau_i$ ) was defined as  $\tau_i = \tau_t - \tau_c$ , where  $\tau_t$  is the total delay time and  $\tau_c$  is the channel charging time. Using  $\tau_i$ , the effective channel electron velocity was derived by  $L_g/\tau_i$ . Table 1 shows the effective channel electron velocity estimated at 25 and  $300^\circ\text{C}$  for an AlGaIn-

Table 1 Effective channel electron velocity of AlGaIn-channel HEMT and GaN-channel HEMT evaluated at  $25^\circ\text{C}$  and at  $300^\circ\text{C}$ .

	$v_{\text{eff}}@25^\circ\text{C}$ ( $10^6\text{cm/s}$ )	$v_{\text{eff}}@300^\circ\text{C}$ ( $10^6\text{cm/s}$ )
AlGaIn channel	2.7	1.7
GaN channel	6.0	1.5

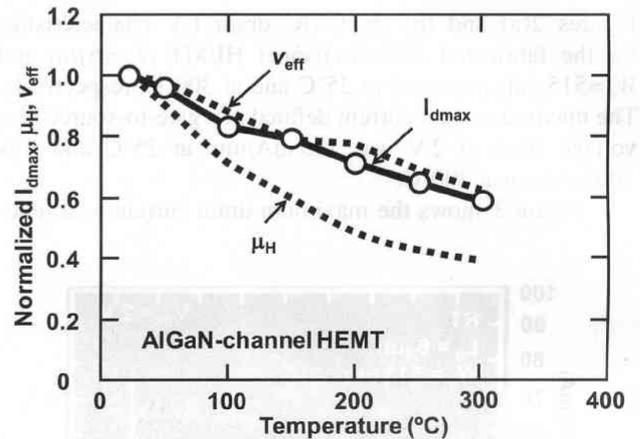


Fig. 6 Normalized maximum drain current, Hall mobility, and effective channel electron velocity ( $v_{\text{eff}}$ ) as a function of temperature for AlGaIn-channel HEMT.

channel HEMT and for a GaN-channel HEMT. Although the effective channel electron velocity for the GaN-channel HEMT was about 2 times larger at  $25^\circ\text{C}$ , its magnitude was reversed at  $300^\circ\text{C}$ , suggesting that the reversal of the maximum drain current observed at high temperatures, as shown in Fig. 3, was closely related to the temperature dependence of the effective channel electron velocity that was predominantly governed by the high-field saturation velocity.

Figure 6 shows the maximum drain current, Hall mobility, and effective electron velocity as a function of temperature for the AlGaIn-channel HEMT. All values were normalized to those at  $25^\circ\text{C}$ . It is evident that the degradation in the drain current at elevated temperatures corresponds well to the temperature dependence of the effective electron velocity in the channel and does not show good correlation with the temperature dependence of the channel mobility. These results suggest that the reduced degradation in the maximum drain current at high temperatures was mainly dominated by the temperature dependence of the effective electron velocity in the AlGaIn channel. At present, it is not well understood why the effective electron velocity in AlGaIn exhibited reduced degradation as compared to the temperature dependence of the channel mobility. In our devices with  $L_g=2\mu\text{m}$ , all the channel region under the gate would not be in such enough high electric fields to allow all the channel electrons moving with a high-field (saturated)

electron velocity. The slight deviation observed between the temperature dependences of effective electron velocity and maximum drain current, in Fig. 6, may be due to the fact that some of the channel electrons are still affected by the low-field mobility though they are mostly accelerated by the high electric field in the channel region. To clarify the mechanism in more details, it would be desirable to perform similar experiments on shorter gate length HEMTs, where high-field transport is dominant under the whole gate region.

#### 4. Conclusion

An AlGa<sub>N</sub>-channel HEMT has been fabricated on a free-standing AlN substrate and its device performance has been compared to that for a standard AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT. At room temperature, the conventional Ga<sub>N</sub>-channel HEMT exhibited much better performances in most of the device properties, such as maximum drain current, channel electron mobility, current gain cutoff frequency, and effective electron velocity, than those for the AlGa<sub>N</sub>-channel HEMT. However, the difference in those properties was reduced with increasing the device temperature. At 300°C, the magnitude of the maximum drain current and the current gain cutoff frequency was reversed between the two devices, showing that an AlGa<sub>N</sub>-channel HEMT is superior to a conventional AlGa<sub>N</sub>/Ga<sub>N</sub> HEMT at high temperatures. These results indicate that an AlGa<sub>N</sub>-channel HEMT on an AlN substrate is promising for high-temperature electronics applications at more than 300°C. The superior high-temperature performance of AlGa<sub>N</sub>-channel HEMTs is presumed to be due to the comparatively small temperature dependence in electron drift velocity at high fields.

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