Comparative high-temperature DC characterization of HEMTs with GaN and AlGaN channel layers

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Abstract

AlGaN-channel high-electron mobility transistors (HEMTs) on an AlN substrate have been fabricated for the first time. A maximum saturation current of 0.13A/mm at V_{GS} =2V and a maximum transconductance of 25mS/mm were obtained. DC characteristics of AlGaN-channel HEMT and GaN-channel HEMT were comparatively examined at temperatures ranging from RT to 300ºC. The temperature coefficient of drain current for the AlGaN-channel HEMT was about one half of that for GaN-channel HEMT. These results indicate that AlGaN-channel HEMTs grown on an AlN substrate are promising candidates for high-temperature electronics applications.

INTRODUCTION

High-electron mobility transistors (HEMTs) are attracting great interest for high-frequency and high-power device applications. GaN and related nitride semiconductors are expected as key materials for high-voltage and high-frequency HEMT devices. Recently, reflecting the wide bandgap nature of these materials, studies on high-temperature device operation have received increased interest in view of possible device application under elevated temperatures. Gaska et al. [1] reported that AlGaN/GaN HEMTs on a SiC substrate exhibited a 50% decrease in the saturated drain current by increasing temperature up to 250ºC. They also observed stable DC performance up to 300ºC without noticeable irreversible change. Maeda et al. [2] reported excellent drain current saturation and sufficient pinch-off characteristics up to 400ºC for AlGaN/GaN HEMTs on a SiC substrate. They observed a decrease in the saturated drain current by about one-third by increasing temperature from 25 to 400ºC. Daumiller at al. [3] measured I-V characteristics of AlGaN/GaN HEMTs at temperatures up to 800ºC and reported stable device operation without irreversible degradation up to 600ºC. Similarly, Arulkumaran et al. [4] reported recovered drain I-V characteristics upon cooling from 500ºC for AlGaN/GaN HEMTs fabricated on both SiC and sapphire substrates. Tan et al. [5] reported that the temperature dependence of the drain current is dependent on the gate length of AlGaN/GaN HEMTs.

To further improve the performance limitation of nitride-based HEMTs, AlGaN-channel HEMTs have been recently developed. Nanjo et al. [6] was the first to develop AlGaN-channel HEMTs with an Al composition of 0.2, where a drain current density of 0.13A/mm was measured. Subsequently, improved DC performance was reported by the same authors, in which a saturated drain current density of 0.11A/mm and a maximum breakdown voltage of 1650V were achieved with an Al composition of 0.38 [7]. Raman et al. [8] reported a higher drain current density of 0.55A/mm with an Al composition of 0.06 for the AlGaN channel. The device delivered an output power of 4.5W/mm at 4GHz. To date, however, studies on DC characteristics of AlGaN-channel HEMTs at elevated temperatures have not been reported.

In this paper, we describe high-temperature DC performance of AlGaN-channel HEMTs fabricated on an AlN substrate. Saturated drain current density and on-state resistance are estimated for the AlGaN-channel HEMT and are compared with those for the standard AlGaN/GaN HEMT. Superior thermal stability in the DC performance of AlGaN-channel HEMT is demonstrated in the temperature range from RT to 300ºC.

DEVICE STRUCTURE AND FABRICATION PROCESS

Figure 1 shows the schematic diagram of an AlGaN-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 an undoped 600nm AlGaN channel layer with an Al composition of 0.24 and an undoped 21nm AlGaN barrier layer with an Al composition of 0.51. The sheet resistance of an as-grown AlGaN/AlGaN heterojunction estimated on wafer was 1740 Ω/sq.

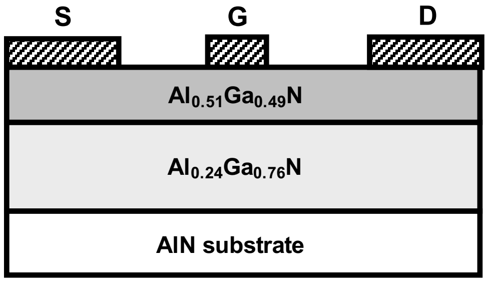


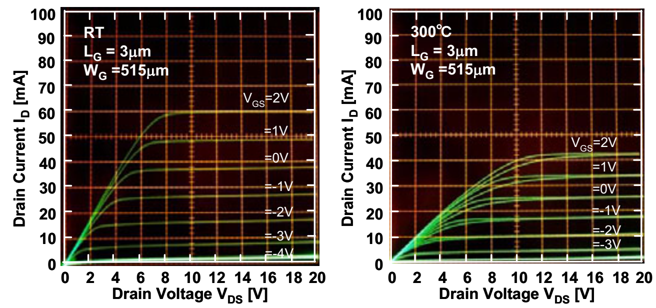
Fig.1 Schematic cross-sectional structure of $Al_{0.51}Ga_{0.49}N/Al_{0.24}Ga_{0.76}N$ HEMT on AlN substrate.

One of the critical process steps in fabricating AlGaN-channel HEMTs is the ohmic contact formation for source and drain electrodes. Preliminary studies indicated that higher-temperature annealing is preferable to achieve good ohmic contacts for AlGaN/AlGaN heterostructures. Since the optimum annealing temperature of Zr/Al/Mo/Au ohmic contacts to AlGaN/GaN is higher than that of Ti/Al/Mo/Au [9], we have chosen Zr/Al/Mo/Au as ohmic contacts for our AlGaN channel heterostructure. Electron-beam evaporation was employed to sequentially deposit Zr, Al, Mo and Au with thicknesses of 15, 60, 35 and 50nm, respectively. Ohmic metals were then annealed by RTA at 950℃ for 30s under an N_2 ambient. Evaporated Ni/Au was used for Schottky gate metallization. The length and width of the gate was 3μm and 515μm, respectively. For comparison, a standard AlGaN/GaN HEMT having same electrode dimensions was fabricated on a Si substrate. The thickness and Al composition for the AlGaN barrier layer were 25nm and 0.25, respectively. No passivation films were used for all the devices.

RESULTS AND DISCUSSION

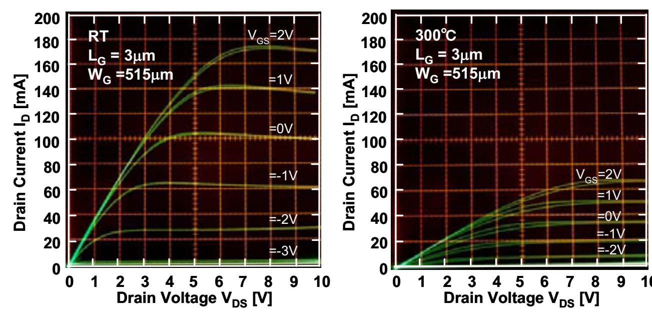
Figures 2 (a) and (b) show drain I-V characteristics of the fabricated AlGaN-channel HEMT measured at room temperature (25ºC) and at 300ºC. Excellent pinch-off and saturation characteristics were observed at both temperatures. At 25ºC, the device exhibited a saturated drain current (I_d) of 0.13A/mm and a maximum transconductance (g_m) of 25mS/mm with a threshold voltage of -3.8V. The estimated on-state resistance (R_{ON}) was 60Ωmm. When the temperature was raised to 300ºC, the device showed a saturated drain current of 0.082A/mm, a maximum transconductance of 17mS/mm, a threshold voltage of -3.6V and an on-state resistance of 103Ωmm.

Figures 3 (a) and (b) show drain I-V characteristics of the fabricated standard AlGaN/GaN HEMT on a Si substrate measured at 25 and 300ºC. Although the saturated drain current and transconductance of the GaN-channel HEMT is evidently much better than those of the AlGaN channel device at 25ºC, i.e., I_d=0.33A/mm, g_m=78mS/mm, the degradation rate in DC characteristics with the increase in temperature from 25 to 300ºC is much worse, resulting in I_d=0.13A/mm and g_m=29mS/mm at 300ºC.



(a) (b)

Fig.2 Drain I-V characteristics for AlGaN-channel HEMT with Al composition of 0.24 measured at RT (a) and at 300ºC (b).



(a) (b)

Fig.3 Drain I-V characteristics for GaN-channel HEMT measured at RT (a) and at 300ºC (b).

Figure 4 shows the drain current (measured at V_{DS}=10V and V_{GS}=0V) normalized to its value at 25ºC as a function of temperature for AlGaN-channel and GaN-channel HEMTs. A gradual decrease in the drain current with increasing temperature is observed in both devices. However, it is clear that the amount of current degradation for the AlGaN-channel HEMT is about one half of that for the GaN-channel HEMT.

Figure 5 shows the on-state resistance normalized to its value at 25ºC as a function of temperature for AlGaN-channel and GaN-channel HEMTs. It is observed that R_{ON} exhibits an almost linear increase with increasing temperature and that the increase rate of R_{ON} for the GaN-channel device is more than 3 times larger than that for the AlGaN-channel device. Since R_{ON} is composed of source and drain contact resistances (R_C), parasitic source resistance (R_S), channel resistance (R_{CH}) and parasitic drain resistance

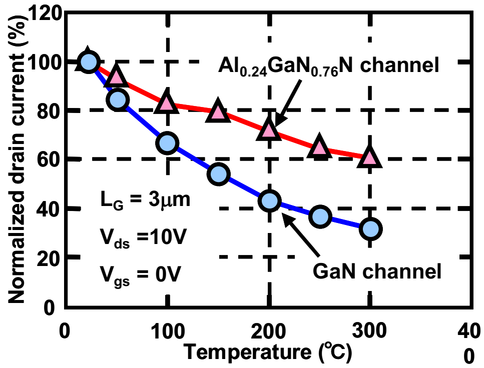


Fig.4 Normalized drain current as a function of temperature for AlGaN-channel HEMT and for GaN-channel HEMT.

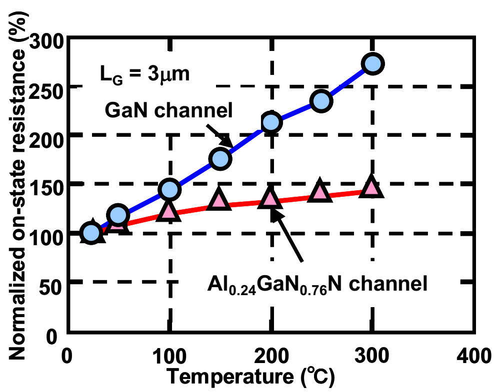


Fig.5 Normalized on-state resistance as a function of temperature for AlGaN-channel HEMT and for GaN-channel HEMT.

(R_D), R_{ON} is expressed as

$$R_{ON} = 2R_C + R_S + R_{CH} + R_D .$$

Experimental measurements on R_C indicated that R_C is almost independent of device temperature for both AlGaN and GaN channel HEMTs. Thus when the measured Hall mobility and the inverse of $(R_{ON} - 2R_C)$ normalized to its value at 25ºC are plotted as a function of temperature, clear correspondence between them is evident, as shown in Fig.6. These results indicate that the temperature dependence of the sum of R_S, R_{CH} and R_D follows that of the mobility in the channel layer.

Figure 7 shows the threshold voltage as a function of temperature for AlGaN-channel and GaN-channel HEMTs. The threshold voltage for the GaN-channel HEMT exhibited a positive shift by 0.6V with increasing temperature up to 300ºC. On the other hand, the AlGaN-channel HEMT

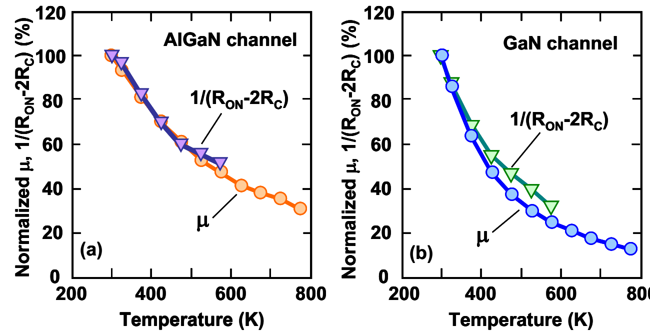


Fig.6 Normalized Hall mobility and the inverse of $(R_{ON} - 2R_C)$ as a function of temperature for AlGaN-channel HEMT (a) and for GaN-channel HEMT (b).

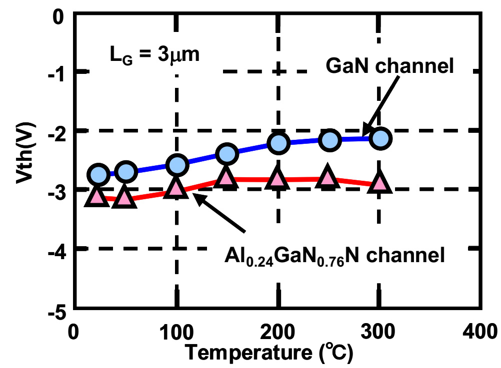


Fig.7 Threshold voltage as a function of temperature for AlGaN-channel HEMT and for GaN-channel HEMT.

exhibited only a small shift of less than 0.2V in the threshold voltage with the increase in temperature, showing that the AlGaN-channel HEMT is more suited for high-temperature operation

CONCLUSIONS

High-temperature DC characteristics of AlGaN-channel HEMT and GaN-channel HEMT were comparatively studied at temperatures ranging from RT to 300ºC. Results indicated that the temperature coefficient of drain current for the AlGaN-channel HEMT was about one half of that for the GaN-channel HEMT. These results indicate that AlGaN-channel HEMTs grown on an AlN substrate are promising for high-temperature electronics applications.

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ACRONYMS

HEMT: High Electron Mobility Transistor
R_{ON}: On-State Resistance
RTA: Rapid Thermal Annealing