# AlN/AlGaN HEMTs on AlN substrate for stable high-temperature operation

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We demonstrate an AlN/AlGaN high-electron-mobility transistor (HEMT) fabricated on a free-standing AlN substrate. A metal stack, composed of Zr/Al/Mo/Au, was found to show low contact resistivity for source and drain ohmic contacts. The fabricated AlN/AlGaN HEMT exhibited a maximum drain current of 38 mA/mm with a threshold voltage of -3.4 V. Negligible drain current degradation was observed at temperatures from 300 to 573 K, demonstrating that our AlN/AlGaN approach on an AlN substrate is promising for stable high-temperature operation.

*Introduction:* An AlGaN/GaN high-electron-mobility transistor (HEMT) is a promising device applicable to high-power, high-voltage, and high-temperature electronic applications [1]. The use of GaN as a channel layer in HEMTs, however, suffers from significant degradation in the drain current at elevated temperatures [2,3]. Nanjo et al. reported the first operation of an AlGaN-channel HEMT on a sapphire substrate, where $Al_{0.2}Ga_{0.8}N$ and $Al_{0.4}Ga_{0.6}N$ were used as a channel layer and a barrier layer, respectively [4]. To increase Al composition in the AlGaN channel layer, Tokuda et al. reported an AlGaN-channel HEMT on a free-standing AlN substrate and demonstrated its superior high-temperature stability by using $Al_{0.51}Ga_{0.49}N$ and $Al_{0.86}Ga_{0.14}N$ as channel and barrier layers, respectively [5]. From these results, further improved stability at high temperatures would be expected by adopting higher Al compositions for both channel and barrier layers. Ti/Al-based ohmic metal stacks have been commonly used to form ohmic contacts on AlGaN/GaN heterostructures. However, it becomes rather difficult to achieve enough low values in the contact resistivity for AlGaN-channel HEMTs. Yafune et al. were the first to apply alloyed ohmic contacts to AlGaN-channel HEMTs using a metal stack of Zr/Al/Mo/Au for an AlGaN barrier layer with an Al composition of 0.86 [6].

In this letter, we describe DC characteristics of a novel AlGaN-channel HEMT fabricated on an AlN substrate. Emphasis is placed on the optimization of ohmic contact resistance utilizing Zr/Al/Mo/Au metal stacks. Excellent stability in DC characteristics at high temperatures is presented for the developed AlN/AlGaN HEMT.

*Experimental procedure:* Fig. 1 shows a cross sectional view of the fabricated AlN/AlGaN HEMT. The epitaxial layers were grown by metalorganic chemical vapor deposition (MOCVD) on a free standing AlN substrate with a dislocation density of less than $10^6$ $cm^{-2}$ [7]. The structure consists of a 200 nm-thick AlN buffer, a 300 nm-thick AlGaN channel layer with an Al composition of 0.6, and a 20 nm-thick AlN barrier layer. Details of the growth procedure have been published elsewhere [8]. All the epitaxial layers were undoped.

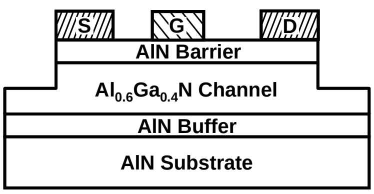


**Fig.1** *Schematic cross section of AlN/AlGaN HEMT fabricated on AlN substrate*

Device processing was started with mesa isolation by $BCl_3/Cl_2$-based reactive ion etching with an etching depth of 100 nm. Ohmic metals of Zr/Al/Mo/Au were deposited by e-beam evaporation followed by rapid thermal annealing (RTA) at temperatures ranging from 900 to 1000 °C for 30 s. The thickness of Zr was varied from 5 to 25 nm and that of Al was varied from 60 to 180 nm. The thicknesses of Mo and Au were fixed at 35 and 50 nm, respectively. The specific contact resistivity was estimated by circular transfer-length method (CTLM). Ni/Au (100/150nm) was used as a Schottky gate metal. The device has a circular pattern with a gate length of 6 µm. The spacing between source and gate and that between gate and drain were 3 and 5 µm, respectively. All the devices were unpassivated.

*Results and Discussion:* Fig. 2 shows the specific contact resistivity of Zr/Al/Mo/Au ohmic contacts as a function of annealing temperature. It was found that the lowest ohmic contact was achieved when the thicknesses of Zr and Al were chosen to be 15 and 120 nm, respectively. After RTA at 850 °C, the sample exhibited strong non-linear I-V characteristics with extremely high resistivity in the low-voltage region. By RTA at more than 900 °C, improved linearity has been observed in the I-V characteristics with rather a low specific contact resistivity of around $10^{-2}$ Ω $cm^2$. The best contact resistivity achieved was $1.9\times10^{-2}$ Ω $cm^2$ after RTA at 950 °C. In our previous study [8], a specific contact resistivity of $4.8\times10^{-2}$ Ω $cm^2$ was attained for an epitaxial structure of $Al_{0.86}Ga_{0.14}N/Al_{0.51}Ga_{0.49}N$ by using Zr/Al/Mo/Au with Zr and Al thicknesses of 15 and 60nm, respectively. These results suggest that a thicker Al thickness in Zr/Al/Mo/Au is beneficial to achieve better ohmic characteristics for higher Al composition in the barrier layer.

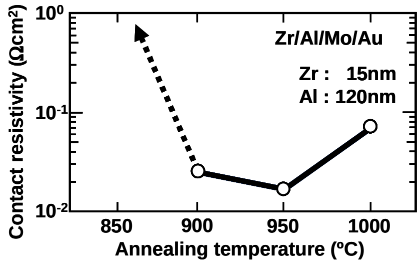


**Fig.2** *Specific contact resistivity as a function of annealing temperature for Zr/Al/Mo/Au metal stack on AlN/AlGaN heterostructure*

Figs. 3 (a) and (b) show drain current-voltage (I-V) characteristics, measure at 300 and 573 K, respectively, for an $AlN/Al_{0.6}Ga_{0.4}N$ HEMT. The threshold voltage was almost unchanged to be -3.4 V both at 300 and 573 K. At 300 K, the device exhibited a maximum drain current ($I_{dmax}$) estimated at Vgs=2 V of 38 mA/mm, a saturation drain current ($I_{dss}$) estimated at Vgs=0 V of 23 mA/mm, and an on-state resistance ($R_{on}$) of 284 Ωmm. When the device temperature was raised to 573 K, the device exhibited $I_{dmax}$, $I_{dss}$, and $R_{on}$ of 40 mA/mm, 22 mA/mm, and 210 Ωmm, respectively. It should be noted that $R_{on}$ is decreased and $I_{dmax}$ is increased with increasing temperatures up to 573 K. Because of the thermionic nature of Zr/Al/Mo/Au ohmic contacts, the contact resistance was improved from 85 Ωmm at 300 K to 42 Ωmm at 573 K, leading to the reduced $R_{on}$ and increased $I_{dmax}$ at elevated temperatures. Using independently estimated sheet resistances of 3800 Ω/ (at 300 K) and 8700 Ω/ (at 573 K) by Hall-effect measurements and a source-to-drain distance of 14 µm, $R_{on}$ was calculated to be 223 Ωmm at 300 K and 206 Ωmm at 573 K. Those calculated values are in reasonable agreement with the measured $R_{on}$ of 284 Ωmm (at 300 K) and 210 Ωmm (at 573 K).

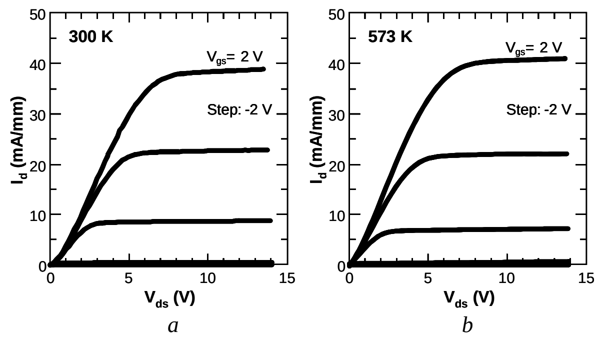


**Fig.3** *Drain I-V characteristics of AlN/AlGaN HEMT*
*a Measured at 300 K*
*b Measured at 573 K*

Fig. 4 shows the drain current measured at Vgs= 0 V as a function of temperature for an $AlN/Al_{0.6}Ga_{0.4}N$ HEMT. Each value of drain current was normalized by its value at 300 K. Also plotted are the results for a standard $Al_{0.25}Ga_{0.75}N/GaN$ HEMT. The degradation ratio in the drain current between 300 and 573 K was only 4% for the $AlN/Al_{0.6}Ga_{0.4}N$ HEMT, while that was as large as 80% for the $Al_{0.25}Ga_{0.75}N/GaN$ HEMT. Hatano et al. reported that at 573 K the effective electron velocity in the $Al_{0.26}Ga_{0.74}N$ channel becomes larger than that for the GaN channel [9]. Therefore, the improved high temperature operation for the $AlN/Al_{0.6}Ga_{0.4}N$ HEMT is not only ascribed to the decreased contact resistivity but also to the small relative degradation in the effective electron velocity. Moreover, the high thermal conductivity of AlN (200 W/m·K) would contribute as a beneficial factor for high temperature operation. The reduced temperature dependence of AlN/AlGaN HEMTs is expected to be particularly important for applications, where no special cooling mechanisms are able to be utilized in the system.

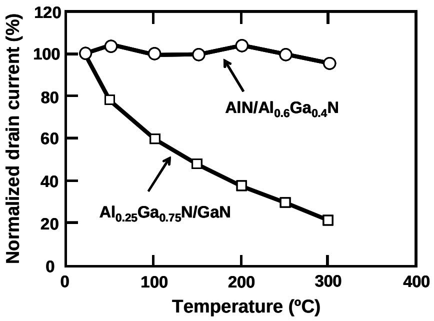


Fig.4 *Temperature dependence of drain current for AlN/AlGaN HEMT. Also plotted is the temperature dependence for standard AlGaN/GaN HEMT*

*Conclusion:* we have developed an AlN/AlGaN HEMT on a free-standing AlN substrate. It was found that a metal stack of Zr/Al/Mo/Au was effective to achieve low ohmic contacts on AlN/AlGaN heterostructures. A contact resistivity of $1.9\times10^{-2}\ \Omega\ cm^2$ was achieved by optimizing the metal thickness of Zr/Al/Mo/Au and by annealing at 950 °C. The fabricated AlN/AlGaN HEMT exhibited a maximum drain current of 38 mA/mm at room temperature and showed only a small decrease by 4 % in the drain current with increasing the device temperature up to 573 K.

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