# Extreme Temperature Operation of Ultra-Wide Bandgap AlGaN High Electron Mobility Transistors

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**Keywords: AlGaN, GaN, HEMT, high temperature**

## Abstract

**$Al_{0.85}Ga_{0.15}N/Al_{0.7}Ga_{0.3}N$ (85/70) High Electron Mobility Transistors (HEMTs) were operated up to 500°C in ambient with only 58% degradation of DC current in I-V measurement relative to 25°C. The low gate leakage current contributed to high gate voltage operation up to 10 V, with $I_{ON}/I_{OFF}$ ratios of $> 2 \times 10^{11}$ and $3 \times 10^{6}$ at 25°C and 500°C, respectively. Gate lag measurements at 100 kHz are identical to DC measurements at room temperature, with only slight degradation upon heating.**

## INTRODUCTION

The wide bandgap materials GaN (3.4 eV) and SiC (3.3 eV) are commonly used in the communication systems supporting our modern digital infrastructure. Moving to the next stage of the information era requires further improvements in high-power switching devices, namely enhancing the breakdown field and environmental operation regime. To satisfy this demand, shifting from traditional GaN-channel HEMTs to ultra-wide bandgap (UWBG) AlGaN-channel HEMTs is an attractive option for improving the power handling of devices under extreme operation [1-6]. The UWBG of $Al_{0.7}Ga_{0.3}N$ (5.7 eV) along with high potential critical breakdown (12.7 MV/cm) leads to a Baliga FOM of 11772 over an order of magnitude improvement over GaN, BFOM of 846.

## DEVICE FABRICATION AND CHARACTERIZATION

The HEMT samples were prepared by metal organic chemical vapor deposition (MOCVD) on sapphire substrates. First, a 1.6 µm AlN nucleation and buffer layer were grown on the substrate. Then a transition layer from 100% Al to 70% Al was grown across 50 nm. The 400 nm unintentionally doped channel layer, $Al_{0.7}Ga_{0.3}N$, was grown next, followed by the 25 nm $Al_{0.85}Ga_{0.15}N$ barrier layer. The barrier layer was doped with Si at $3\times10^{18}$ cm$^{-3}$. Contactless measurement of the 2DEG showed the resistivity to be 2200 Ω/□, combined with CV measurements showing carrier density $n_s = 9\times10^{12}$ cm$^{-2}$. Circular HEMT devices were fabricated with a gate length of 2 µm, and source/drain to gate spacing of 4 µm. The gate had a circumference at its center of 660 µm. Planar Ohmic contacts (Ti/Al/Ni/Au) were deposited and subsequently annealed. The gate was formed by deposition of Ni/Au into an opening on the 100 nm thick SiN dielectric to allow for edge termination (see Fig. 1).

DC characterization was carried out using an Agilent 4156C parameter analyzer. A Tektronix Curve Tracer 370A was used to collect high voltage I-V curves. A Wentworth automated temperature control chuck was used to vary the chuck temperature from room temperature to 500°C.

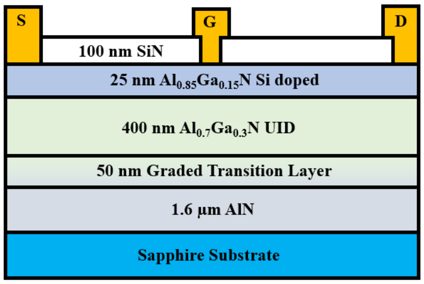

Fig. 1. Device Schematic of $Al_{0.85}Ga_{0.15}N/Al_{0.7}Ga_{0.3}N$ HEMT.

## RESULTS AND DISCUSSION

In Fig 2, typical current-voltage characteristics are shown at from room temperature and 500°C. As the temperature increases, the total current decreases, with 58% degradation from room temperature to 500°C. A high gate voltage of 10 V was possible, as the gate leakage current was minimal (< 100 nA at lower gate voltages). The primary difficulty when fabricating high Al content devices is the Ohmic contact formation. While a slight non-Ohmic nature was noted at room temperature, once the devices were heated to 100°C they had become perfectly Ohmic.

Fig 3. shows that the zero bias Schottky Barrier Height (SBH) increased significantly across the entirety of the

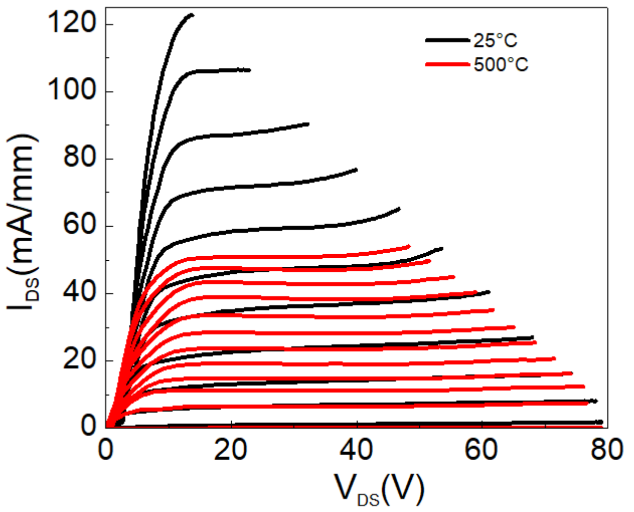

Fig. 2. Current-Voltage characteristics at 25°C and 500°C.

temperature range, illustrating the excellent gate diode characteristics. A high SBH for a gate is necessary for high speed and high current density enhancement mode HEMTs. The high SBH, sufficient barrier layer thickness, and high-quality interface leads to a very small gate leakage current, with a very low probability of tunneling in the 85/70 device. In the traditional GaN HEMT($Al_{0.25}Ga_{0.75}N$/GaN), as the temperature is increased, the thermal energy of the electrons becomes sufficient to induce thermionic field emission and surmount the Schottky barrier due to the barrier height remaining relatively constant across the temperature range.

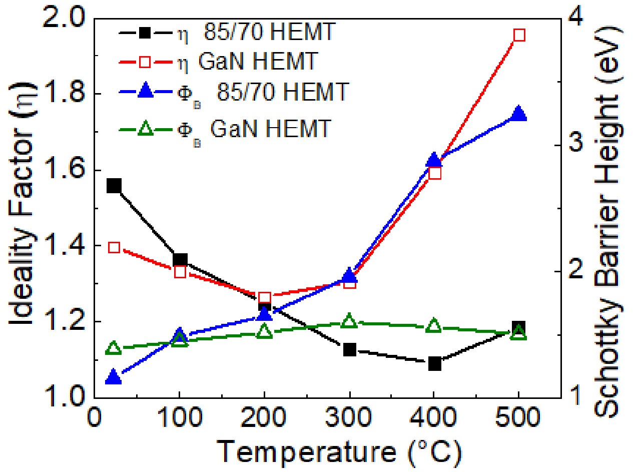

Fig. 3. Ideality Factor and Schottky Barrier Height as a function of temperature for the 85/70 and GaN HEMT.

With such a high SBH and strong DC characteristics at elevated temperature, the pulsed operation of the device is the upmost importance for this material system to find use in high power switching. Gate-lag measurements at 100 kHz and 10% duty were performed across the temperature range, Fig. 4. Pulsed characteristics were ideal even at high temperature and were only slightly reduced under high positive gate biases. First, this result indicates that the high temperature excites

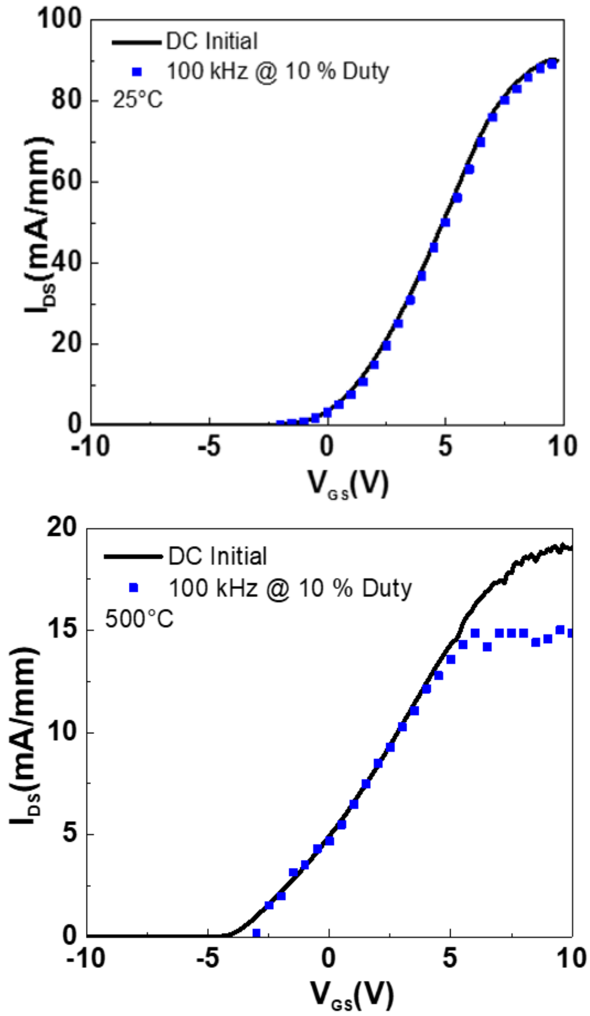

Fig. 4. Gate lag at 25 and 500°C under $V_d$ = 10 V and 100 kHz at 10% duty.

electrons from defects as the supplied thermal energy is now great enough. However, these defects become apparent under pulsed operation due to their long relaxation time. The pulse of reverse voltage (9 μs) refills these electron traps then these traps are unable to relax and release the charge when the device is switched on under positive bias due to the short-time (1 μs). These trapped electrons will act as a virtual gate lowering the forward current. Further exploration into the exact trap levels whether they originate from Ga, Al, or N vacancies are of interest in our future work to improve device reliability for the 85/70 HEMT. The devices in their current can easily be operated with moderate gate voltages and achieve perfect matching to DC performance.

Figure 5 shows the gate-induced drain leakage current as a function of temperature. As the temperature was increased, the gate-induced drain leakage (GIDL) current increased due to activation of traps and electron surface-related hopping conduction. The GIDL current was explored by extraction of its activation energy by assuming an Arrhenius form. Two regimes were found, 100 to 350°C and 350 to 500°C, with activation energies $E_a$ = 0.63 eV and $E_a$ = 0.076 eV, respectively. $E_a$ = 0.63 eV can be viewed as the energy required for the trap-assisted tunneling or trap assisted thermionic emission. For $E_a$ = 0.076 eV, GIDL current is very weakly temperature dependent, indicating that a second mechanism is now predominant, likely band-to-band tunneling.

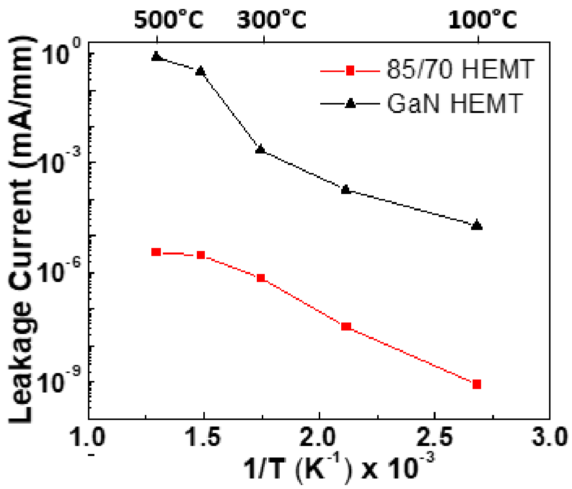

Fig. 5. Arrhenius plot of gate induced leakage current for the 85/70 and GaN HEMT.

One of the main strengths of GaN HEMT is the high electron mobility in the 2DEG. One of the primary issues with GaN HEMT is upon heating, the mobility degrades by multiple orders of magnitude, along with a very large increase in leakage current. At room temperature, the 85/70 HEMT is not able to achieve the same high mobility as traditional GaN; however, the reduction in the mobility at high temperatures is much more modest and reasonable, as shown in Fig 6. Also, the lower mobility is not a concern for the targeted application of low-frequency high-power switching. The high critical electric field ($E_c$) for $Al_{0.7}Ga_{0.3}N$ of > 11.7 MV/cm and smaller mobility reduction greatly improves the 85/ 70 devices lateral figure of merit and Johnson figure of merit at high temperatures.

The mobility was extracted for both devices using low electric field current-voltage characteristics from the equation:

$$\frac{V_{ds}}{I_{ds}} = R_s + R_d + \frac{Ld}{\mu W \varepsilon (V_{gs} - V_{off})}$$

Where $V_{DS}$ and $I_{DS}$ are the drain to source voltage and current, respectively. $R_S$ and $R_D$ are the source and drain resistances, L is the gate length, W is the channel width, d is the thickness of the barrier layer, $\varepsilon$ is the dielectric constant, $V_{GS}$ is the applied gate voltage, and $V_{OFF}$ is the pinchoff voltage. To verify the accuracy of the extracted mobility, room temperature measurements were compared to C-V extraction of mobility. Coltrin et al. modelled the mobility in the 2DEG as a function of aluminum content for our material system [4]. As such, the primary limitation for the mobility at elevated and moderate temperatures is polar optical phonon scattering and at low temperatures ( < 273K) alloy scattering is the dominant mechanism.

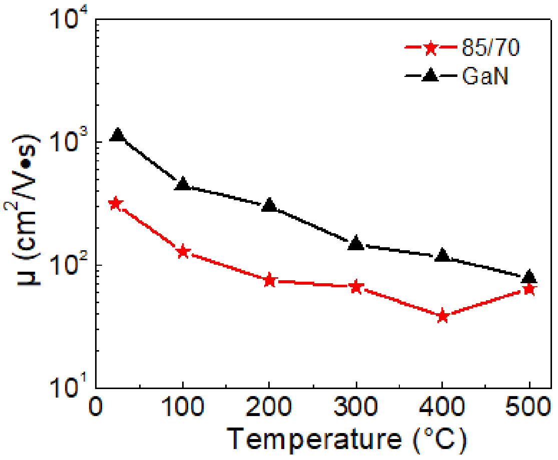

Fig. 6. Electron mobility as a function of temperature for the 85/70 and GaN HEMT.

For true high-power devices, achieving low leakage current is a requirement. As previously mentioned, the 85/70 HEMT had a uniquely high and increasing SBH with temperature. The high barrier height leads to an On/Off ratio in excess of $10^{11}$ at room temperature (see Fig 7). At room temperature and 50°C, we were measurement-limited as the drain leakage current was < 2 fA. With traditional GaN HEMTs, very few reports exist exploring operation above 300°C as the devices become incredibly leaky, with low On/Off ratios of ~$10^4$, and are not feasibly operable under such conditions. Thus, AlGaN HEMTs provide a method for which cooling requirements may be even less stringent as the operable regime is much larger.

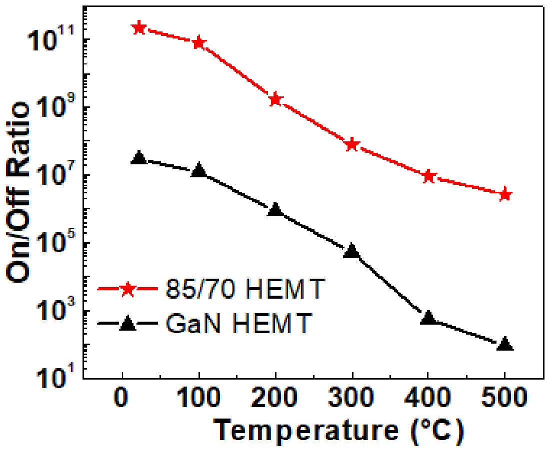

Fig. 7. On/Off ratio as a function of operating temperature for the 85/70 and GaN HEMT.

## CONCLUSIONS

$Al_{0.85}Ga_{0.15}N/Al_{0.7}Ga_{0.3}N$ HEMTs demonstrate a unique ability to operate with full gate control up to 10 V at 500°C. Low gate leakage current was observed due to the insulator-like properties of the barrier layer. The high SBH, which increases with temperature, can mitigate leakage current due to the increased thermal energy of channel electrons. The high $I_{ON}/I_{OFF}$ ratio of $2 \times 10^{11}$ and $3 \times 10^{6}$ at 25°C and 500°C, respectively, were extracted and emphasize the potential for high-power application of this novel HEMT structure. The nearly-ideal pulsed IV characteristics further demonstrate the potential for AlGaN channel HEMTs in power switching applications.

## ACKNOWLEDGEMENTS

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC (NTESS), a wholly owned subsidiary of Honeywell Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. The views expressed in the article do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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## ACRONYMS

HEMT: High Electron Mobility Transistors
2DEG: 2D Electron Gas
GaN: Gallium Nitride
AlGaN: Aluminum Gallium Nitride