GaN hot electron transistors: From ballistic to coherent

J. W. Daulton*1,2, R. J. Molnar1, J. A. Brinkerhoff3, Z. C. Adamson2, M. A. Hollis1, A. Zaslavsky2
1MIT Lincoln Laboratory, Lexington, MA 02421, USA  
2 School of Engineering, Brown University, Providence, RI 02912, USA  
Email: jeffrey_daulton@brown.edu

Abstract — Previously we demonstrated high-current, high-gain III-nitride hot electron transistors (HETs), utilizing collimated electron injection and an undoped base region. Here, we compare the behavior of these devices from 300 to 77 and 4.2 K to elucidate the role of hot electron scattering. Under cryogenic operation and Gummel biasing, we obtain a maximum current gain of 3.5 at a collector current density of 1.35 MA/cm², limited by the onset of intervalley electron transfer, and common-emitter current gain β > 20. Our results point to the promise of nitride HETs for realizing the long-proposed coherent transistor.

Keywords—hot electron transistor, ballistic transport, polarization doping, atomic layer etching, coherent transistor

I. INTRODUCTION

Gallium arsenide-based hot electron transistors (HETs), where energetic electrons traverse the base ballistically and surmount the base-collector barrier, attracted significant research effort throughout the 1980’s [1, 2]. However, interest in these devices eventually waned due to the low Γ to L intervalley energy spacing in GaAs, which limited ballistic transport and gain. More recently, progress in III-nitride materials growth, where the large intervalvaly Γ to M-L energy separation of approximately 2 eV allows for significantly higher injected electron energy before the onset of intervalley scattering, has led several groups to explore nitride-based HETs [3, 4], although until recently reported devices were limited to relatively low current densities and low gain.

Recently, we reported on room-temperature GaN-based HETs with high common-emitter current gain β = Ic/Ib > 20 and high-current operation [5]. In our design, the electron beam was collimated by injecting into the base from a quantized subband formed in the emitter, whereas the base was doped via polarization only, eliminating the ionized impurity scattering that significantly reduced electron mean-free path in most earlier demonstrations. In this work, we extend the room temperature testing to 77 and 4.2 K, demonstrating minimal temperature sensitivity in the J-V characteristics and transfer coefficient α = Ic/Ib, as well as record Ic current density in excess of 1 MA/cm².

Further, we have observed the onset of intervalley electron transfer, as manifested in the Gummel characteristics by the rollover in current gain. Our high α and suppressed scattering point to the potential of nitride HETs for experimentally realizing the long-proposed coherent transistor [6] that requires fully ballistic transport at cryogenic temperatures.

II. DEVICE DESIGN AND FABRICATION

Our device structure is shown schematically in Fig. 1(a) together with a top view of the device with a ~1.3 μm² emitter area. Device design simulations were carried out in Synopsys Sentaurus to ensure the formation of a high-density 2D electron gas (2DEG) in the base, with electron injection energy under active biasing not to exceed the Γ to M-L intervalley energy spacing.

![Fig. 1. (a) Schematic cross-section of device (with only one of two symmetric base contacts shown) together with a top-view photograph; (b) self-consistent band diagram for VBE = 2 V, VCB = 0 (Gummel) and 2 V (active biasing).](image)

The resulting epitaxial design was grown by MOCVD on 2” sapphire wafers. The emitter stack consisted of a highly-doped (~10^19 cm⁻³) emitter cap, with a triangular quantum well formed by polarization fields at the interface of an undoped graded AlGaN emitter and an ultrathin 1.5 nm AlN tunnel barrier. The base consisted of a narrow 10 nm undoped GaN layer with a designed 2DEG density of ~3.5×10^12 cm⁻² formed due to polarization doping at the emitter-base interface. The collector...
region consisted of a graded AlGaN base-collector transition layer to an Al$_{0.12}$Ga$_{0.88}$N collector barrier. The resulting band diagram, including the quantized injection subband in the emitter and the $I_C$ and $I_B$ electron current components, is illustrated in Fig. 1(b). The fabrication details, including damage-free BCl$_3$/O$_2$ atomic layer etching to enable low-resistance sidewall contacts to the 2DEG in the base, as well as contact metallization and active-area isolation steps, are available in [5].

### III. Electrical Characterization

Two HET devices (T1 and T2) were characterized at 300 K and then prepared for low-temperature device testing by wire-bonding to a DIMM PCB configured for immersion in liquid N$_2$ and He. Figure 2(a) shows the 300 K Gummel plot of device T2 up to $I_C$ current compliance limit of 12 mA, slightly under $\sim 1$ MA/cm$^2$, set to protect the device from emitter metal burnout. Gummel current gain $\beta$ continues increasing and shows no sign of rollover by the time it reaches a maximum value of 2.5 at $V_{BE} = 4.6$ V. Figure 2(b) shows the reproducibility of the two devices, with minimal deviation in transfer coefficient $\alpha$: we observe a slightly higher $\alpha$ in T1 over the entire bias range after onset of hot electron injection. We attribute this slight difference to dislocations within each device, as our measured dislocation density [5] of $\sim 5 \times 10^9$ cm$^{-2}$ results in an average of 5-10 dislocations per emitter, with significant device-to-device variation.

![Fig. 2.](image)

**Fig. 2.** (a) Room-temperature Gummel ($V_{CB} = 0$) plot of device T2, including all current components and current gain $\beta$; (b) transfer coefficient $\alpha$ for devices T1 and T2 and their difference, showing reproducible device behavior.

The Gummel condition transfer coefficients of device T2 at 300, 77 and 4.2 K are shown in Fig. 3. At low $V_{BE}$ we observe a delayed onset of hot electron injection, which we attribute to suppressed thermionic filling of the quantized emitter subband. However, once the low-temperature injection commences at $V_{BE} \sim 1.1$ V, there is a barely noticeable increase in sharpness for 4.2 K compared to 77 K. As the 77 K condition is closest to the peak of sapphire’s thermal conductivity, we risked increasing the current compliance to measure the device up to $V_{EB} = 6$ V, where $I_C$ density reached 1.35 MA/cm$^2$ and Gummel gain reached 3.5. We also observed a clear rollover in the differential gain $dI_C/dI_B$ at $V_{EB} = 5.1$ V, due to the onset of intervalley scattering. Measured active mode common-emitter current gain reached $\beta > 20$ for $V_{BE} = 2$ V and $V_{CB} = 2.2$ V active biasing (see Fig. 1(b) for active mode biasing band diagram).

The temperature independence of the transfer coefficient at cryogenic temperatures indicates that the dominant scattering mechanism depends on the electron temperature rather than lattice temperature. This is consistent with LO-phonon emission [4, 7] being the dominant scattering mechanism at cryogenic temperatures in the absence of impurity scattering, with $\hbar\omega_{LO} = 92$ meV in GaN.

The high measured values of $\alpha$ despite the dominant role of LO-phonon emission indicate that the nitride HET is a promising platform for the coherent transistor [6], where gain peaks above the usual transit time $t_1$ cutoff are predicted as long as the electron transport through the base is fully ballistic. This will require redesigning the electron injection energy to fall below $\hbar\omega_{LO} = 92$ meV.

![Fig. 3.](image)

**Fig. 3.** Transfer ratio $\alpha$ for device T2 at 300, 77 and 4.2 K; differential transfer ratio $dI_C/dI_B$ at 77 K shows onset of intervalley scattering at high $V_{BE}$.

### Conclusions

We have fabricated a III-nitride HET with temperature-insensitive device characteristics between 77 and 4.2 K, including common-emitter gain >20 and high ballistic transfer ratio and Gummel gain, at current densities above 1 MA/cm$^2$ up to the onset of intervalley scattering. This suggests the potential of redesigned nitride HETs for the experimental demonstration of the proposed coherent transistor [6], provided electron injection energy is maintained below the LO-phonon energy of 92 meV.

### References


