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Current gain above 10 in sub-10 nm base III-Nitride tunneling hot electron transistors with GaN/AlN emitter

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We report on a tunneling hot electron transistor amplifier with common-emitter current gain greater than 10 at a collector current density in excess of 40 kA/cm². The use of a wide-bandgap GaN/AlN (111 nm/2.5 nm) emitter was found to greatly improve injection efficiency of the emitter and reduce cold electron leakage. With an ultra-thin (8 nm) base, 93% of the injected hot electrons were collected, enabling a common-emitter current gain up to 14.5. This work improves understanding of the quasi-ballistic hot electron transport and may impact the development of high speed devices based on unipolar hot electron transport. Published by AIP Publishing.

GaN high electron mobility transistors (HEMTs) have the ability to deliver high power density for high frequency applications. Lateral scaling and Ohmic contact regrowth has enabled high cutoff (fT) and maximum oscillation frequency (fmax) demonstrations.1–3 However, the frequency and power density of lateral HEMTs face some fundamental physical limits. To achieve amplification at higher frequency, the power gain at high frequency needs to be increased by reducing transit and RC delays, while maintaining low output conductance. In lateral structures, reducing the transit delay, which is done by shrinking lateral dimensions, also leads to an increase in the output conductance, which degrades high frequency power gain.4,5 A second limitation of lateral transistors is related to thermal management. While wide band gap materials, such as GaN, operate at higher power density than traditional GaAs and Si amplifiers due to the larger band gap and sheet charge density, they do not have significantly higher thermal conductivity. As a result, in systems with highly scaled 2D electron gases, such as AlGaN/GaN HEMTs, the energy dissipation in a thin sheet-like volume leads to significant local heating and temperature rise.

Vertical geometry transistors have advantages both in terms of scaling and thermal management, and are therefore especially favorable for wide band gap semiconductors. For vertical devices, electron transport can be defined by heterojunction growth at a scale shorter than 10 nm, and output conductance can be controlled through doping and epitaxial engineering. Since power dissipation in a vertical device occurs over a volume rather than in a 2D sheet, the local temperature rise is not as significant as in the lateral case.

The most common high frequency vertical devices, heterojunction bipolar transistors (HBTs), are difficult to achieve in III-Nitride system due to the low conductivity of p-type GaN, caused by low hole mobility.6,7 In this work, therefore, we investigate vertical transistors based on unipolar electron transport—tunneling hot electron transistor (THETA). THETA had been previously demonstrated in GaAs systems,8–10 and current gain in excess of 10 had been achieved with wide-bandgap AlSbAs emitter at room temperature.11 GaN THETA has been reported in recent years but the current gain in these devices has remained relatively low.12–16 In this work, we demonstrate GaN THETA operating with common-emitter current gain above 10 achieved by implementing polarization engineered barriers in the emitter–base and base–collector junctions.

The THETA device shown in Fig. 1(a) is composed of n++ GaN emitter contact layer, i-GaN/i-AlN emitter–base barrier, n++ GaN base, i-AlGaN base–collector barrier, and n GaN subcollector. Under emitter–base bias V_{EB} < 0, a quasi mono-energetic hot electron beam (emitter current, I_E) is injected from the emitter, and transferred to the subcollector (collector current, I_C) via quasi-ballistic transport, with a small fraction of hot electrons relaxed into the base (base current, I_B). The base current is thus determined by the electrons thermalized within the base and/or reflected by the base–collector barrier. By applying sufficiently high

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emitter–base bias, $I_C$ exceeds $I_B$, giving rise to a common-emitter current gain.

One of the main challenges of the GaN THETA has always been the leakage through random-alloy AlGaN barriers. Introduction of polarization for the base–collector diode has suppressed the leakage and enabled common-emitter operation. However, the current gain was found to be limited by the leakage through the emitter–base barrier. When the electrons penetrate into the base through the emitter–base barrier, their energy is insufficient to overcome the base–collector barrier, causing rise in the base current. Here we report suppression of leakage current using unintentionally doped (UID) GaN/AlN for the emitter–base barrier, and ensuing common-emitter current gain in excess of 10.

The THETA structure was grown on Ga-polar free-standing GaN substrates (St. Gobain, Si-doping $3 \times 10^{18} \text{cm}^{-3}$, threading dislocation density (TDD) $\sim 5 \times 10^7 \text{cm}^{-2}$) by plasma-assisted molecular beam epitaxy (PA-MBE). The sample has an emitter contact layer of 20 nm n++ GaN (Si-doping $5 \times 10^{19} \text{cm}^{-3}$), an emitter–base barrier of unintentionally doped (UID) GaN/AlN (111/2.5 nm), a base layer of 8 nm n++ GaN (Si-doping $2 \times 10^{19} \text{cm}^{-3}$), a spacer of 4 nm UID GaN, a base–collector barrier of 6 nm 15% AlGaN/5 nm 11% to 15% AlGaN (from top to bottom)/65 nm 16% AlGaN/28 nm UID GaN, and subcollector of 210 nm n+ GaN (1 $\times 10^{19} \text{cm}^{-3}$ Si-doped), as shown in Fig. 1(a). Both emitter and base Ohmic contacts were formed by evaporating Al/Ni/Au/Ni stacks. Inductively coupled plasma reactive ion etching (ICP-RIE) with BCl$_3$/Cl$_2$/Ar chemistry was used to recess to base region for tunneling contact to the base, and to form mesa isolation. Subcollector Ohmic contact was formed by Indium dot on the backside of the samples. The devices had an emitter area of $\sim 10 \mu\text{m}^2$ and device area of $\sim 100 \mu\text{m}^2$.

The band diagram of the GaN THETA is shown in Fig. 1(b). Polarization charges are induced at the UID GaN/AlN interface which pull up the conduction band of the thick UID GaN layer, leading to the formation of a wide electrostatic emitter–base barrier to suppress low energy electron leakage. Therefore, a quasi-mono energetic hot electron beam is tunnel-injected over the emitter–base barrier as shown in the inset of Fig. 1(b). The effect of using polarization engineered barrier to prevent cold carrier injection is evident from the two-terminal $I-V$ characteristics of the emitter–base diode shown in Fig. 2(a). The $I-V$ curve showed a turn-on voltage around 4.5 V, at which bias the conduction band in the 111 nm UID GaN region is flattened and electrons are allowed to tunnel through the 2.5 nm of AlN into the base. The maximum current density flowing through the emitter–base diode reached 17 kA/cm$^2$ at $V_{BE}$ up to 15 V.

This behavior shows a clear contrast with the previously investigated emitter–base diode without polarization engineering that had not shown significant rectification. The two terminal $I-V$ characteristics of the base–collector diode (Fig. 2(b)) also showed relatively low leakage current density of less than 100 A/cm$^2$ at base–collector bias $-8 \mathrm{~V} < V_{CB} < 3 \mathrm{~V}$. The contact and sheet resistance of the base have been determined from the transmission line measurements (TLM) and found to be 3.8 $\Omega \cdot \text{mm}$ and 2 k$\Omega$/sq, respectively.

Fig. 3(a) shows the common-base characteristics of THETA taken at $V_{CB} = -7 \mathrm{~V}$. For $V_{BE} < 10 \mathrm{~V}$, low leakage going into the base was observed. As voltage increases, the tunneling through AlN commences, and hot electrons are injected into the base. Most of these carriers reach the collector, but some end up in the base due to scattering and quantum reflection; hence both base and collector currents increase rapidly. As tunneling current surpasses the leakage, the onset of DC gain (when $\beta = I_C/I_B$ exceeds unity) occurs at $V_{BE}$ around 10 V. $\beta$ continues to increase until it reaches 23 at $V_{BE} = 11 \mathrm{~V}$.

Once the fact that most of the hot carriers injected into the base do find their way into the collector had been verified, the common-emitter output characteristics were measured as shown in Fig. 3(b). The DC gain $\beta$ increased with the base current $I_B$ and a peak $\beta$ value of 14.5 was measured at $I_B = 0.32 \mathrm{~mA}$ ($J_B = 3.2 \text{mA/cm}^2$) and $V_{CE} = 3.5 \text{V}$, with $I_C = 4.66 \text{mA}$ ($J_C = 46.6 \text{mA/cm}^2$). This indicates that 93% of electrons (estimated as $I_C/(I_C + I_B)$) injected into the base region reached the collector, despite scattering in the base and quantum reflections at the collector barrier—a most significant result achieved by using narrow base and polarization engineered barriers.

Fig. 4 shows the differential current gain ($h_{fe} = dI_C/dI_B$) and transconductance ($g_m = dI_C/dV_{BE}$) extracted from Fig. 3(b). As $I_B$ increased to 0.26 mA, $h_{fe}$ reached 40 at $V_{CE} = 3.5 \text{V}$. The corresponding $g_m$ was $30 \text{kS/cm}^2$ (3 mS). An additional improvement in these two parameters may be attained if the base thickness is further reduced. It should be noted that increased doping will lead to the upsurge of scattering of hot electrons by cold electrons residing near the bottom of the conduction band in the base, which will reduce the current gain. This scattering mechanism has been shown from our preliminary analysis to be dominant in the highly-doped base; hence, the limit to which the base thickness can be reduced requires further in-depth study.

With the high current gain achieved, the only remaining barrier separating GaN THETA from high power applications...
is high output conductance \( g_0 = \frac{\partial I_C}{\partial V_{CE}} \) evident in the common-emitter characteristics of Fig. 3(b). This output conductance as high as 2 mS makes voltage gain hard to achieve. There are many factors that can cause the high output conductance. First of all, there is a modulation of the height of the collector barrier\(^{11}\) that causes increase in the current gain, essentially an equivalent of the early effect in bipolar transistors. An improved design of the base–collector barrier should mitigate this problem. Furthermore, engineering the emitter–base barrier to make the injected electron beam more collimated could also reduce the barrier lowering effect. A second factor behind high \( g_0 \) is the fact that the applied field modifies the emitter/base barriers causing increase in the emitter current as carriers in the base fail to completely screen out the field—this situation is analogous to the one arising in vacuum triodes where it is solved by introducing a fourth, screening electrode in tetrodes. Similar strategy can be pursued by introducing additional doped regions in the collector/base junction to screen out the voltage applied to the collector.

In conclusion, common-emitter current gain up to 14.5 was demonstrated for a GaN-based THETA, by using a polarization induced GaN/AlN emitter barrier to inject hot electrons. The results indicate that 93% of the electrons are collected after being injected into the base from the emitter contact layer, despite multiple scattering processes and quantum reflections. The work presented here has demonstrated the potential of quasi-ballistic devices based on gallium nitride.

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**FIG. 3.** Three-terminal characteristics in: (a) common-base configuration at \( V_{BE} = 8–11\) V and \( V_{CE} = 7\) V and (b) common-emitter configuration at \( V_{CE} = 2–3.5\) V and \( I_b = 0–0.32\) mA.

**FIG. 4.** (a) Differential current gain \( h_{fe} \) and (b) transconductance \( g_m \) extracted from common-emitter characteristics in Fig. 3.

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