Current Gain > 10 in III-Nitride Tunneling Hot Electron Transistors

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Introduction: We report on demonstration of GaN tunneling hot electron transistors (THETA) with dc current gain up to 14.5 in common-emitter configuration, which is highest value reported to date in GaN-based hot electron transistors. THETA is a promising candidate to obtain vertical high frequency transistors in GaN. In a THETA, an emitter-base (EB) barrier is applied to tunnel-inject hot electron beams, and a base-collector (BC) barrier filter cold electrons leak from the base [1]. Under forward operation condition emitter-base bias $V_{EB} < 0$, the injected hot electrons quasi-ballistically transit the base and collector layers, and contribute to the collector current (I_C). The electrons relaxed due to scattering in the base and quantum reflection at the BC heterojunction contribute to the base current (I_B). When the EB junction is sufficiently biased, I_C exceeds I_B, resulting in a current gain. In this work, the transistors were designed to have unintentionally doped (UID) GaN/AlN emitter barrier to block low energy electrons, ultra-thin base (<10 nm) to enhance ballistic transport, and polarization-engineered BC barrier to limit leakage.

Design and Fabrication: Two structures were grown by plasma assisted molecular beam epitaxy, consisting of a UID GaN/AlN emitter barrier with different thickness (20 and 111 nm). The UID GaN emitter barrier was used to suppress low energy electrons injection into the base (Fig. 1(a)). The polarization sheet charge at the UID GaN/AlN interface raises the conduction band of the UID GaN, leading to the formation of a wide electrostatic barrier to block the low energy electrons. An 8nm base layer was used in both samples to minimize hot electron relaxation in the base layer. Al/Ni/Au/Ni was deposited as emitter and base metal stacks. The devices were isolated to a depth of 100 nm with mesa area of 100 μm^2.

Experimental Results: Polarization engineered barrier [2] prevents cold carrier injection into the base, which is evident from the EB diode I-V (Fig 2). The emitter-base diode characteristics showed an increase of turn-on voltage from 3 V to 4.5 V with increasing the barrier thickness from 20 to 111 nm. This is due to the increased bias at which the conduction band of UID GaN is flattened and electrons are allowed to tunnel through the 2.5 nm of AlN into the base. The injection current density through the EB diode was > 10 kA/cm^2, and the leakage through the BC diode was < 1 kA/cm^2 for both samples. The base contact and sheet resistances were 3.8 Ω·mm and 2 kΩ/sq from TLM measurement.

Common-emitter output characteristics were measured (Fig. 3). Modulation in collector current I_C was observed with increasing base current I_B for both samples. The current gain β (= I_C/I_B) was measured up to 2.7 and 9 for emitter thickness of 20 and 111 nm at V_{CE} = 3 V. The increase in the current gain is attributed to the increase in the emitter injection efficiency with thicker UID emitter barrier, which is also evident from two-terminal I-V in Fig. 2. The peak value of β of 14.5 for 111 nm UID was measured at I_B = 0.32 mA, with output current I_C = 4.66 mA (corresponding to J_B = 3.2 kA/cm^2 and J_C = 46.6 kA/cm^2). This indicates 93% of electrons injected from the emitter reached the collector after transit across the base (~73% for 20 nm UID), despite scattering in the base and quantum reflection at the BC barrier. Transconductance (g_m) characterized by sweeping base-emitter bias V_{BE} while keeping constant V_{CE} is shown in Fig. 4. Positive g_m confirms the transistor operations for both samples, which are ~5 and ~10 kS/cm^2 for 20 and 111 nm emitter barrier, respectively. The larger g_m in the 111 nm barrier sample indicates more electrons were transferred to the collector due to higher emitter injection efficiency by polarization engineering. No saturation was observed, indicating the hot electron velocity was modulated by base-collector bias. Current gain demonstrated in the above cases show the potential of the GaN THETA for high frequency power amplifiers.

Conclusion: DC current gain greater than 10 was demonstrated in GaN tunneling hot electron transistors, by using a polarization engineered GaN/AlN emitter barrier to inject hot electrons. 93% of the injected electrons were collected, despite scattering processes and quantum reflection. The work may provide insights into other high speed devices based on quasi-ballistic hot electron transport in III-Nitride system. This work is funded by Office of Naval Research under the DATE MURI project (Program manager: Dr. Paul Maki).

Reference

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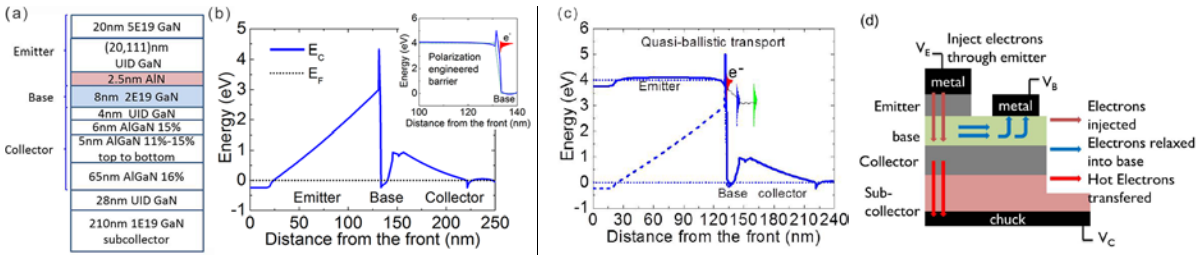

Fig. 1 (a) Epitaxial structures, (b) equilibrium band diagram, (c) band diagram under bias emitter-base bias V_{BE}<0, and (d) operation principle of GaN hot electron transitor (HET).

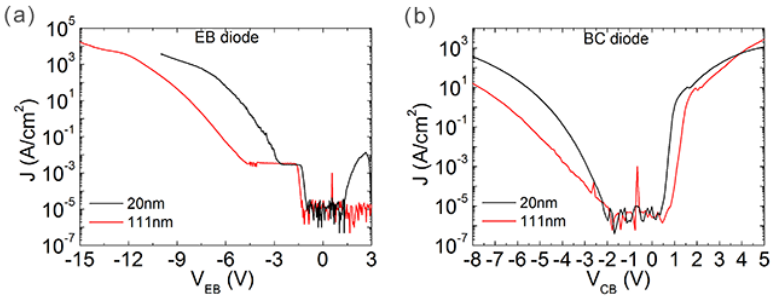

Fig. 2 Two-terminal I-V characteristics: (a) emitter-base diode and (b) base-collector diode.

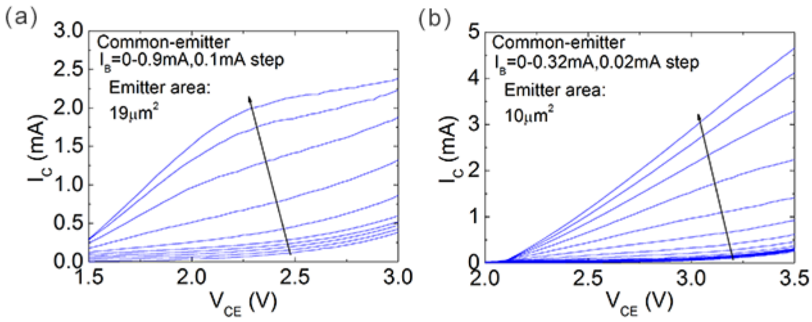

Fig. 3 Common-emitter output characteristics with (a) 20nm and (b) 111nm emitter barrier thickness.

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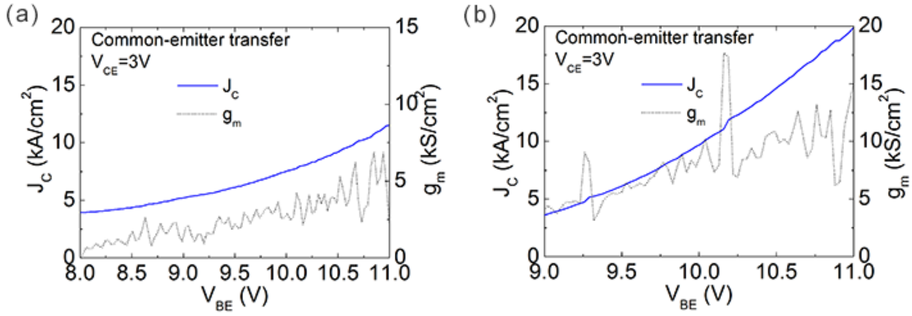

Fig. 4 Common-emitter transfer characteristics with (a) 20nm and (b) 111nm emitter barrier thicknes.