Emerging III-Nitride Devices for Terahertz Electronics

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Principal Investigator(s): Huili Grace Xing, Debdeep Jena

User(s): Jimy Encomendero, Austin Hickman, Samuel Bader

Affiliation(s): Electrical and Computer Engineering, Cornell University

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Contact: grace.xing@cornell.edu, djena@cornell.edu, jje64@cornell.edu, alh288@cornell.edu, sjb353@cornell.edu

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Abstract:

In the present work, we report the design, fabrication and demonstration of emerging III-nitride electronic devices that hold the promise for the manufacture of high-power ultra-fast electronic amplifiers and complementary logic based solely on nitride semiconductors. A novel design of a quantum well transistor is presented and its power performance is assessed employing the Johnson figure-of-merit. The complementary III-nitride p-channel transistor is also studied here, showing record performance in terms of on-current and carrier density. Finally, vertical resonant tunneling transport is also studied in III-nitride heterostructures. By introducing an analytical quantum transport model for III-nitride resonant tunneling diodes (RTDs), we reproduce all the features of the experimentally measured tunneling current. These advances pave the way for the design all-nitride high-power ultra-fast amplifiers and digital integrated circuits.

Summary of Research:

III-nitride materials have emerged as a promising platform for the development of electronic devices capable of meeting the increasing demand for high-power ultra-fast amplifiers for communication networks, and complementary transistors for computing applications. This revolutionary family of wide bandgap semiconductors has already enabled the manufacture of high-power electronic switches, harnessing the internal polarization fields for the generation of highly dense two-dimensional electron gases (2DEG) [1]. However, digital applications require the manufacture of the complementary 2D hole gas (2DHG) switch, which would unleash the full potential of III-nitride semiconductors for digital applications.

In this report, we present important advances in the design, fabrication and understanding III-nitride switches that can be employed for the development of the nitride-based complementary logic for computation, and ultra-fast resonant tunneling diodes (RTDs) that hold the promise for the development of future nitride-based terahertz electronics.

Polarization-induced high-electron mobility transistors (HEMTs) are the workhorse of nitride electronics. HEMTs harness the high electron density of the 2DEG induced at the AlGaN/GaN heterointerfaces.

In the present work, we report a novel design in which a 2DEG is engineered employing AlN as the buffer layer, thus taking advantage of the higher thermal conductivity of the AlN platform. The 2DEG confinement is provided by a 30-nm GaN quantum well sandwiched between the AlN buffer region and a 2-nm AlN top barrier as shown in Figure 1(a). Transistors are fabricated employing a realigned last-gate process with non-alloyed ohmic contacts [2]. Figure 1(b) shows the output characteristics measured at room temperature, revealing a saturation current of 2A/mm and a low on-resistance of 1.3 Ωmm. The transfer curve for this quantum-well HEMT design is displayed in Figure 1(c), showing a current modulation that spans four orders of magnitude with a peak transconductance of 0.6 S/mm. To assess the high-power performance of these devices, breakdown voltage is measured in multiple devices, resulting in a maximum breakdown voltage of 591 Volts.

In addition to III-nitride quantum well HEMTs, the complementary p-type transistor, enabled solely by polarization engineering, is also introduced here. The heterostructure is grown by molecular beam epitaxy (MBE) atop an AlN-template substrate [3]. The MBE-grown layers comprise an AlN buffer layer, an unintentionally (UID)-doped GaN layer extending 5 nm and a 10 nm p-type GaN layer that facilitates the formation of ohmic contacts [See Figure 2(a)]. Enhancement mode p-channel field-effect transistors (pFETs) are fabricated employing a gate-recess process. The transistor characteristics are displayed in Figure

2(b), revealing a record-high on-current of 10 mA/mm and a 640-Ωmm on-resistance. Figures 2(c) shows that the drain current is modulated over four orders of magnitude with a maximum transconductance of 1.5 mS/mm. These results constitute a significant improvement in state-of-art III-nitride pFETs, raising hopes for the demonstration of nitride-based digital ICs.

So far we have discussed the DC operation of III-nitride switches, however high-data rate communication networks also require ultra-fast amplifiers that operate at frequencies approaching the terahertz band. To push the cutoff frequencies of III-nitride high electron mobility transistors (HEMTs) towards this frequency band, parasitic management techniques and highly-scaled fabrication processes have been recently employed [4,5]. However, amplification at frequencies > 1 THz is yet to be demonstrated; in this scenario, alternative gain mechanisms such as resonant tunneling injection, have been proposed to achieve terahertz power amplification [6]. The recent successful engineering of resonant tunneling injection in III-nitride heterostructures [7] has led to an invigorated effort to harness the multiple advantages of nitride-based resonant tunneling devices. Because of their noncentrosymmetric crystal structure, sheets of polarization charge are induced at the heterointerfaces of nitride heterostructures, which lead to a redistribution of free carriers across the active region and surrounding contacts. To get a further insight into the effects of the internal polarization fields, we have recently introduced a quantum transport model that captures the physics of resonant tunneling transport across polar heterostructures.

To experimentally study resonant tunneling transport, we fabricate a series of resonant tunneling diodes (RTDs) with the device structures shown in Figure 3(a). Reflection high-energy electron diffraction (RHEED) is employed to monitor the incorporation of single atomic monolayers to the AlN tunneling barriers [8]. Devices are fabricated employing a self-aligned process and the current-voltage characteristics are measured at room temperature as shown in Figure 3(b). Clear and repeatable negative differential conductance is measured in each of the fabricated samples. Figure 3(b) shown the exponential relationship between the barrier thickness and the resonant tunneling current. Finally, we develop a comprehensive quantum transport model that completely captures all the experimentally measured features of the tunneling current. This model provides a clear insight into the polar RTD current-voltage characteristics and its connection with the heterostructure design parameters. This theory can be employed for the design of nitride resonant tunneling devices exhibiting efficient current injection and improved tunneling dynamics as required in practical applications.

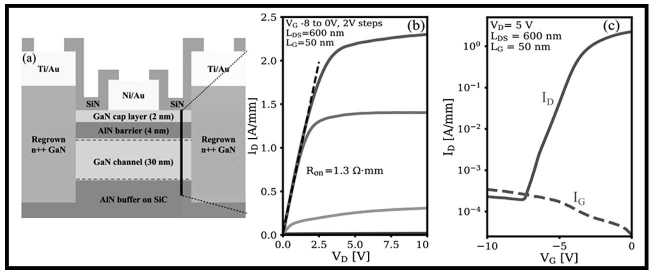

Figure 1: (a) Schematic cross section of the quantum well high-electron mobility transistor (HEMT). (b) and (c) Output and transfer characteristics of the device fabricated at CNF.

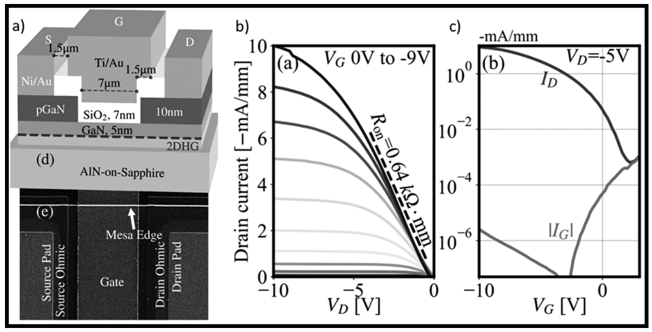

Figure 2: (a) Schematic cross section of the III-nitride p-type field effect transistor (pFET) fabricated in CNF. (b) Room-temperature current-voltage output characteristics show a record-high saturation current of 10 mA/mm and low on-resistance. (c) Transfer characteristics showing four orders of drain current modulation and a peak transconductance of 1.6 mS/mm.

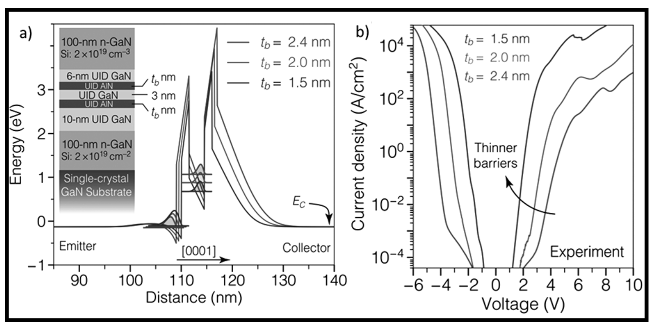

Figure 3: (a) Schematic cross section and band diagram of three resonant tunneling diodes grown by molecular beam epitaxy on single-crystal GaN substrates. (b) Room-temperature current-voltage characteristics for each of the fabricated diodes showing the exponential modulation of the tunneling current as a function of barrier thickness.

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