Nitrogen Polar III-Nitride Resonant Tunneling Diodes

CNF Project Number: 2801-19

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Primary Source(s) of Research Funding: NSF

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Primary CNF Tools Used: Veeco AFM, ABM contact aligner, YES asher, CVC SC4500 odd-hour evaporator, PT770 etcher, P10 and P7 profilometer, Oxford ALD, Oxford 81 etcher, AJA sputter deposition

ELECTRONICS

Abstract:

We report the engineering of resonant tunneling transport in polar III-nitride heterostructures grown along the [000-1] direction of single-crystal GaN substrates. The double-barrier structures, grown by molecular beam epitaxy (MBE), consist of a 3-nm-thick GaN quantum well flanked by two 2.2-nm AlN tunneling barriers. Room temperature electronic transport reveals a peak current density of ~ 7.8 kA/cm^2, measured in multiple resonant tunneling diodes (RTDs) with mesa areas between 36 and 144 μm^2. Electronic quantum interference is confirmed by the presence of repeatable room-temperature negative differential conductance (NDC) under reverse bias injection. The polarization-induced threshold voltage, characteristic in polar RTDs, is also measured at ~ +4.2V. When the devices are biased within the NDC region, microwave electronic oscillations are generated in the external circuit. Owing to the highly non-linear current-voltage characteristics, the oscillatory signal contains not only the fundamental frequency at 10.7 MHz, but also multiple harmonics up to the fifth overtone. These results constitute the first demonstration of robust resonant tunneling injection in III-Nitride N-polar RTDs capable of AC power generation.

Summary of Research:

The recent demonstration of resonant tunneling transport in GaN/AlN heterostructures [1-4] has reignited interest in harnessing this quantum transport regime for the development of ultrafast high-power electronic and photonic devices. Featuring a wide and tunable band gap spanning several electron-volts, III-Nitride heterostructures stand out as a highly versatile platform for tailoring electronic states via quantum confinement. This advantage, coupled with their high breakdown electric-fields, high thermal conductivities, and high longitudinal optical (LO) phonon energies, make nitride materials a promising platform for the development of ultra-fast electronic oscillators and high-power intersubband lasers.

These new functionalities stem from the possibility of engineering ultra-fast carrier injection into discrete energy levels via resonant tunneling, thereby enabling electronic and optical gain over a wide range of frequencies. In non-centrosymmetric semiconductors, however, the engineering of quantum-confined electronic states via heterostructure design, results not only in a discontinuous energy band profile, but also generates built-in polarization charges, whose spatial distribution lacks inversion symmetry [3,5]. Therefore, in the case of Ga-polar RTDs—grown along the [0001] direction—electrons injected from the emitter side undergo enhanced quantum interference effects compared to carriers injected from the collector contact. These natural broken symmetry effects can be exploited as an additional degree of freedom for the realization of novel device functionalities. In this scenario, nitrogen-polar RTDs—grown along the [000-1] direction—offer the possibility of placing the emitter electrode on the top of the resonant tunneling structure, facilitating its integration with other materials such as ferromagnets and superconductors. Despite these advantages, N-polar RTDs have not been demonstrated so far. In this work, we report the growth, fabrication, and transport characteristics of the first N-polar GaN/AlN RTD, exhibiting robust negative differential conductance (NDC) at room temperature [5].

Molecular beam epitaxy (MBE) is employed to grow the GaN/AlN double-barrier resonant tunneling structures under metal-rich growth conditions atop a N-polar single-crystal n-type GaN substrates [6]. The structure consists of a 3 nm GaN quantum well flanked by two 2.2 nm AlN barriers that are sandwiched by heavily doped n-type GaN

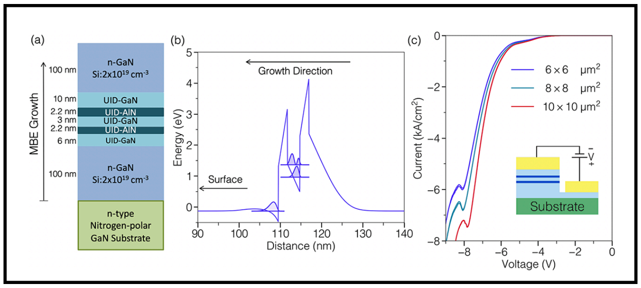

Figure 1: (a) Schematic of the nitrogen-polar RTD structure grown by molecular beam epitaxy. The structure consists of a 3 nm GaN quantum well flanked by two 2.2 nm AlN barriers that are sandwiched by heavily doped n-type GaN contact layers. (b) The band diagram of the structure shows the corresponding energies and wavefunctions of the resonant tunneling levels. (c) Current-voltage characteristics are measured at room temperature, revealing a region of negative differential conductance.

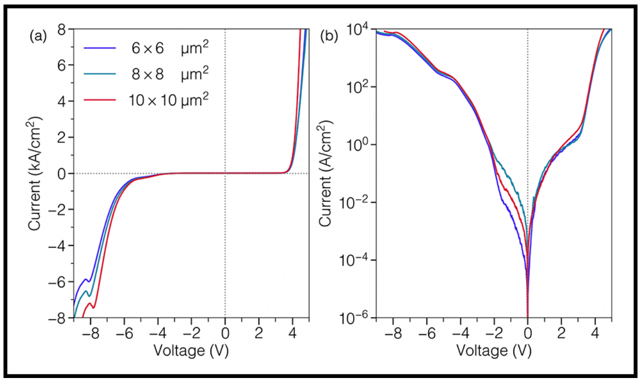

Figure 2: Electronic transport is measured at room temperature in multiple devices with different areas and under both bias polarities. (a) The linear plot shows the onset of negative differential conductance when the diode is biased at ~ -7.8 V, driving a peak tunneling current of ~ 7.8 kA/cm². Under forward bias, the polarization-induced threshold voltage is measured at ~ +4.2 V. (c) The logarithmic plot shows the highly asymmetric exponential modulation of the tunneling current.

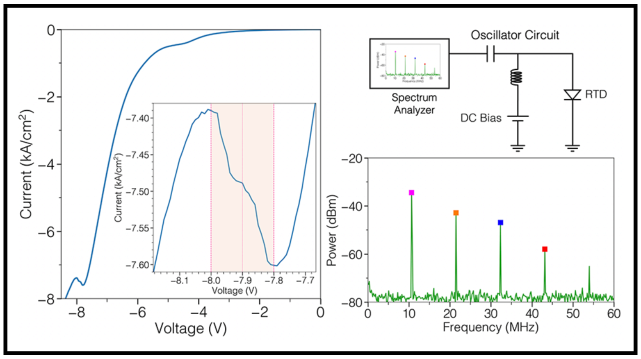

Figure 3: Nitrogen-polar RTD electronic oscillator. When the RTD is biased within the negative differential conductance (NDC) region, AC oscillations build up in the circuit. A bias tee and spectrum analyzer are employed to measure the spectrum of the AC signal. Owing to the highly non-linear characteristics of the NDC region, we measured not only the fundamental frequency at 10.7 MHz, but also multiple harmonics up to the fifth overtone.

layers. *In situ* reflection high-energy electron diffraction (RHEED) showed a (3×3) surface reconstruction at low temperature after growth, indicating the conservation of the nitrogen polarity throughout the whole epitaxial process.

Sharp heterointerfaces are confirmed by the pronounced interference fringes of the symmetric X-ray diffraction (XRD) pattern. The sample also reveals smooth surface morphology with clear atomic steps. After growth, RTDs are fabricated by conventional contact lithography, reactive ion etching, and electron-beam metal evaporation.

Electronic transport is measured at room temperature, revealing negative differential conductance (NDC) due to resonant tunneling injection, in multiple devices with different mesa areas. Under reverse bias, the diodes drive a peak tunneling current of ~ 7.8 kA/cm² at a resonant bias of ~ -7.8V, consistent with the energy alignment between the emitter states and the resonant level in the GaN quantum well.

Under forward bias, the polarization-induced threshold voltage is measured at ~ +4.2V. When the device is biased in the NDC-region, room-temperature electronic oscillations are generated, attesting to the robustness of the resonant tunneling phenomena [4]. Owing to the highly non-linear characteristics of the NDC region, the oscillatory signal contains not only the fundamental frequency at 10.7 MHz, but also multiple harmonics up to the fifth overtone.

These results constitute the first demonstration of robust resonant tunneling injection in III-Nitride N-polar RTDs capable of AC power generation.

References:

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