Room Temperature Microwave Oscillators Enabled by Resonant Tunneling Transport in III-Nitride Heterostructures

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Abstract:

In the present work, we report III-Nitride resonant tunneling diodes (RTDs) operating at room temperature, which exhibit record-high peak current densities up to ~ 220 kA/cm². When the diodes are biased within the negative differential conductance (NDC) region, self-oscillations build up in the biasing circuit. A maximum frequency of oscillation close to 1 GHz is reported. The oscillatory signal and output power are studied in two different RTD designs, showing that their robust negative dynamic conductance can be effectively used as a gain element in high-frequency electronic oscillators.

Summary of Research:

Electronic devices based on III-Nitride semiconductors have emerged as potential solutions to meet the increasing demand for active terahertz (THz) components, due to their high electron velocity, high two-dimensional (2D) electron gas density and high thermal conductivity [1-3]. Toward this end, scaling strategies and parasitic management techniques have been successfully employed to push the cut-off frequencies of III-Nitride high electron mobility transistors (HEMTs) close to the border of the THz band [2,3]. In spite of these advances, amplification at frequencies > 1 THz is yet to be demonstrated. In this context, alternative gain mechanisms such as 2D plasma-waves excited via resonant tunneling injection, have been proposed as a means to engineer THz power amplification [4]. However, resonant tunneling transport across III-Nitride heterostructures has remained an open problem until very recently.

It has been only during the last two years that repeatable resonant tunneling transport was successfully demonstrated in III-Nitride quantum heterostructures [5,6]. Last year, we reported resonant tunneling injection both into the ground state as well as into the first excited state of GaN/AlN resonant tunneling diodes (RTDs) [6]. Furthermore, by precise control over the barrier thickness, peak current densities were enhanced from ~ 6.4 kA/cm² up to ~ 26 kA/cm², raising hopes for the demonstration of high-power RTD oscillators and room temperature THz QCLs.

In the present work, we report III-Nitride RTDs operating at room temperature, which exhibit record-high peak current densities up to ~ 220 kA/cm². When the diodes are biased within the negative differential conductance (NDC) region, self-oscillations build up in the biasing circuit. A maximum frequency of oscillation close to 1 GHz is reported. The oscillatory signal and output power are studied in two different RTD designs, showing that their robust negative dynamic conductance can be effectively used as gain element in high-frequency electronic oscillators.

The device structure of the two different RTD designs are displayed in Figure 1. These heterostructures, grown by molecular beam epitaxy (MBE), were fabricated into diodes using contact lithography, metal evaporation and dry etching processes at the Cornell NanoScale Facility (CNF). The main differences between these diodes are the quantum well width and the extension of the spacer regions next to each of the tunneling barriers (See Figure 1). The incorporation of the desired number of monolayers in the barriers and quantum well was confirmed using high angle annular dark-field (HAADF) scanning transmission electron (STEM) microscopy, as shown in Figure 2.

The typical room temperature current-voltage (I-V) characteristics of the devices are displayed in Figure 3. Both RTDs present a characteristic resonant tunneling peak, driving ~ 180 and ~ 6.4 kA/cm², respectively.

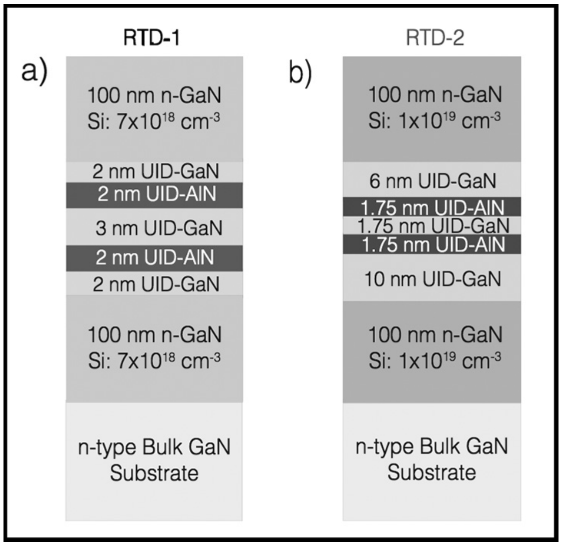

Figure 1: Schematic cross section of the double barrier heterostructures grown by molecular beam epitaxy on single-crystal n-type GaN substrates.

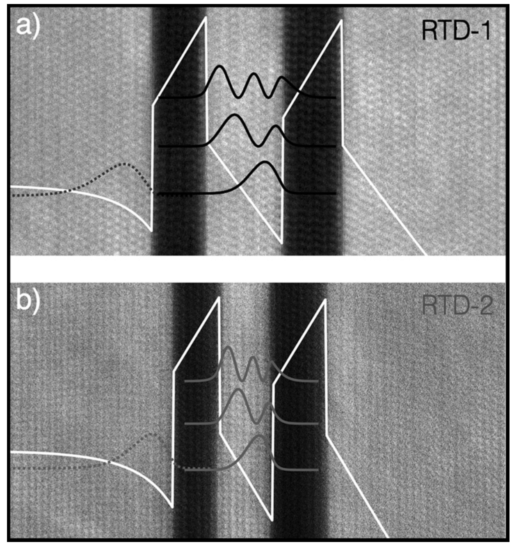

Figure 2: High angle annular dark-field (HAADF) scanning transmission electron microscopy (STEM) images of each of the RTD's active regions. The overlay shows the conduction band profile as well as the confined quantum states.

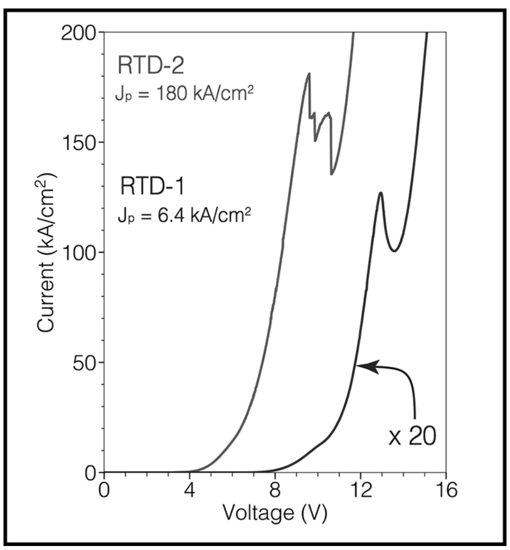

Figure 3: Room temperature current-voltage characteristics of the GaN/AlN RTDs shown in Figure 1. The peak current densities are ~ 180 kA/cm² and ~ 6.4 kA/cm².

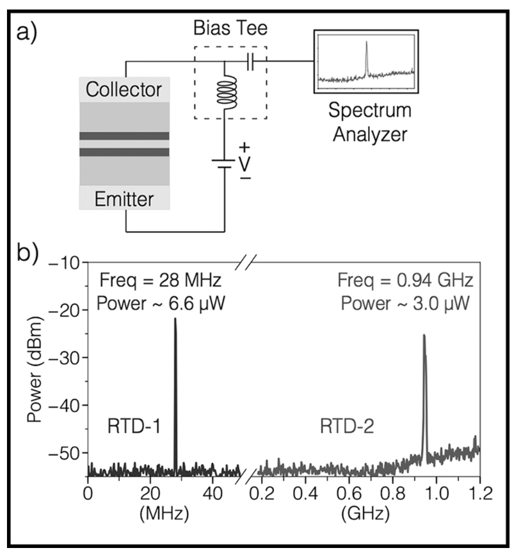

Figure 4: (a) Diagram of the circuit employed to measure the oscillatory signal using a spectrum analyzer. (b) Power spectral density emitted by each of the III-Nitride RTD oscillators.

Microwave oscillators are assembled by connecting the RTDs to a spectrum analyzer using a bias tee and coaxial cables as shown in Figure 4(a). The output power spectrum of each oscillator is displayed in Figure 4(b), showing that a maximum frequency of oscillation of ~ 0.94 GHz is produced by the high-current density RTD, generating ~ 3.0 μW of output power. Using an equivalent RTD circuit model, it is shown that the oscillation frequency is limited by the time constant of the external circuit instead of the tunneling time of the RTDs. These results show the great potential of III-Nitride RTDs for the realization of high-frequency electronic oscillators.

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