Reliable GaN-based Resonant Tunneling Diodes with Reproducible Room-temperature Negative Differential Resistance

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ABSTRACT

Resonant tunneling diode (RTD) is an electronic device embodying a unique quantum-interference phenomenon: negative differential resistance (NDR). Compared to other negative resistance devices such as (Esaki) tunnel and transferred-electron devices, RTDs operate much faster and at higher temperatures. III-nitride materials, composed of AlGaInN alloys, have wide bandgap, high carrier mobility and thermal stability; making them ideal for high power high frequency RTDs. Moreover, larger conduction band discontinuity promise higher NDR than other materials (such as GaAs) and room-temperature operation. However, earlier efforts on GaN-based RTD structures have failed to achieve a reliable and reproducible NDR. Recently, we have demonstrated for the first time that minimizing dislocation density and eliminating the piezoelectric fields enable reliable and reproducible NDR in GaN-based RTDs even at room temperature. Observation of NDR under both forward and reverse bias as well as at room and low temperatures attribute the NDR behaviour to quantum tunneling. This demonstration marks an important milestone in exploring III-nitride quantum devices, and will pave the way towards fundamental quantum transport studies as well as for high frequency optoelectronic devices such as terahertz emitters based on oscillators and cascading structures.

Keywords: resonant tunneling diode, negative differential resistance, GaN, piezoelectric field, dislocation

1. INTRODUCTION

Terahertz (THz) (3 mm to 30 μm) regime has promising applications in various fields such as information and communications technology; biology and medical sciences; homeland security; and ultrafast computing1,2. Lying in the margin of electronic and photonic technologies, THz waves are a big challenge to generate – creating the so-called “THz gap”. There exist two technology roadmaps for THz generation in semiconductor devices: From the low side of THz frequency, electronics-based devices; and from the high side, photonics-based ones. Benefits of resonant tunneling diodes (RTDs) are twofold. They not only can generate THz waves via electronic oscillation but also enable THz quantum cascade laser (QCL) development via subsidiary quantum transport studies. For instance, GaAs-based RTDs can generate THz waves3-4 as well as the understanding of the quantum transport mechanisms within RTDs enable GaAs-based THz QCLs1,2.

RTDs possess a unique quantum-interference characteristic called negative differential resistance (NDR), which is macroscopically identified in device I-V characteristics as decrease in current with increase in voltage5. NDR6, an example of quantum-mechanical tunneling phenomenon in ultrathin structures6, is what is employed in the generation and detection of THz waves1,3 and what inspires novel electronic devices such as hot-electron transistors7. Based on the fastest way of carrier transport, tunneling6, the inherit speed of an RTD is on the order of hundred femtoseconds8. This makes the response of tunneling devices to be limited by the time required to charge the device capacitance through parasitic series resistance (i.e. of the contacts). RTDs, compared to other negative resistance devices such as (Esaki) tunnel and transferred-electron devices (i.e. Gunn diode, Thyristor, and Impact ionization avalanche transit-time diode), possess lower junction capacitance (due to relatively lower doping levels) enabling them operate at higher oscillating frequencies. Since the first demonstration of RTDs9, the performance of these quantum devices have been investigated and improved further10 to extend NDR towards room temperature, which broadened the applications. In spite of these...
advances, the current bottlenecks of conventional (such as GaAs-based) RTDs are the upper frequency limit, output power and operating temperature.

Recently, III-nitrides have gained interest for intersubband (ISB) devices. This is because large electron effective mass \( m^* \approx 0.2-0.3 m_0 \) and longitudinal optical phonon energy (\( \sim 90 \) meV) enable ultrafast ISB relaxation offering very high speed ISB devices. Room temperature THz emitters such as RTD oscillators and QCLs\(^6\) are of particular interest for fulfilling the THz gap. Wide bandgap, large conduction band discontinuity (\( \sim 2.1 \) eV in AlN/GaN)\(^7\), high carrier mobility and thermal stability make AlGaN/GaN material system benign solution for high power high frequency room temperature ISB devices.

Various groups have studied GaN-based RTD structures grown by molecular beam epitaxy\(^1\), \(^2\), \(^3\), \(^4\), \(^5\), \(^6\), \(^7\), \(^8\), \(^9\). Recently, we have studied similar structures by metal-organic chemical vapour deposition (MOCVD)\(^10\), \(^11\). However, in all these early studies, after the initial I-V measurement, the NDR degraded leaving dominant exponential I-V behaviour in the consequent measurement. These attempts to achieve a reliable and reproducible NDR included decreasing the template dislocation density (via freestanding (FS) c-plane GaN substrates\(^1\) or lateral epitaxial overgrowth GaN templates on sapphire\(^1\), \(^2\)), improving active layer quality (via lowering the aluminium content from 100% to 70% in Al\(_x\)Ga\(_{1-x}\)N barriers\(^1\)), and decreasing the active device size (mesa diameters of 40-200 µm\(^1\), \(^2\), \(^3\), \(15 \) µm\(^4\), \(6 \) µm\(^5\), \(5 \) µm\(^6\), and <4 µm\(^7\)). The instability and degradation of NDR were attributed to scattering and trapping in dislocations and to piezoelectric field related electron accumulation\(^1\), \(^2\), \(^3\), \(^4\), \(^5\), \(^6\), \(^7\), \(^8\). Conventional choice of substrates such as sapphire have high lattice-mismatch with GaN leading to high density of dislocations (\( > 10^7 \) cm\(^{-2}\)) in all these studies. Based on these earlier research efforts, it is clear that minimizing the dislocation density is essential to achieve reproducible NDR behaviour in RTD structures. One way to reduce dislocation densities significantly (\(<10^5 \) cm\(^{-2}\)) is employment of GaN FS substrates.

In addition to minimizing the density of dislocation propagating from substrate, we have to minimize the dislocation generation during the heteroepitaxy of barrier-well structures. The active layer of a double barrier (DB) RTD is composed of a narrower bandgap material sandwiched between wider bandgap materials; thus, an inherit lattice mismatch between materials is almost inevitable. The critical thickness (above which dislocations are generated) is inversely proportional to aluminium content for GaN homoepitaxial growth\(^2\). Thus, there is a critical thickness of the barrier for each barrier aluminium content and DB layer needs to be designed considering material quality.

We have recently investigated FS GaN substrates for ultraviolet detectors and showed that FS substrates improve detection characteristics with respect to sapphire substrates\(^1\), \(^2\). Our further studies comparing the polar (c-plane) and nonpolar (m-plane) FS GaN substrates identifies the clear effect of piezoelectric fields on the optical properties of AlGaN/GaN superlattices\(^4\). All these works\(^5\) motivated us to investigate the GaN-based RTD structures grown on polar and nonpolar FS GaN substrates.

Our work on FS substrates have shown that very low dislocation densities (\(<10^5 \) cm\(^{-2}\)) are essential to observe reproducible negative differential resistance in double barrier RTDs\(^6\). Our experimental findings agree well with recent theoretical studies pointing out that dislocation densities lower than \(<10^6 \) cm\(^{-2}\) are essential for reliability\(^7\). Experimentally improving the reliability of the NDR required further material engineering to eliminate the piezoelectric fields and hence the band-bending related 2D electron gas at the double barrier hetero-interfaces\(^8\). Moreover, carrier injection scheme is improved for better carrier injection and to minimize the sidewall effects (sidewall effects are much more dominant in smaller diameter devices due to increased surface-to-volume ratio).

In summary, by proper material, structure, and device engineering, we have demonstrated GaN-based RTDs to have NDR at reverse and forward biases and at room and low temperature for the first time\(^6\). Recently, other groups employing nanostructures\(^9\) for reduced dislocation density and freestanding substrates with reduced piezoelectricity through cubic phase\(^10\) have shown NDR in GaN-based double barrier RTD structures at low and room temperatures, respectively. All these works motivate for further material and design engineering to further our understanding of GaN-based quantum devices.
2. DESIGN

An RTD is conventionally composed of heavily-doped \((10^{19} \text{ cm}^{-3})\) contact layers (such as n-GaN) surrounding an active layer. The active layer consists of a narrower bandgap material (such as GaN) sandwiched between wider bandgap materials (such as AlGaN). This active layer arrangement (such as AlGaN/GaN/AlGaN, seen in Fig. 1b) traps the electrons and forms a discrete electronic state confined in the narrower bandgap material (i.e. GaN) below the energy level of the wider bandgap material (i.e. AlGaN) conduction band. Hence, the narrower bandgap material acts as a quantum well whereas wider bandgap materials act as barriers to electron transport (seen in Fig. 1b). The barriers are kept of finite width to ensure electron transport via quantum tunneling.

Simulations solving Poisson's and Schrödinger's equations are employed to plot the band structure of the double barrier structures. Polarization fields are calculated and taken into account during simulations. Carrier concentrations are calculated using the Boltzmann approximation, and for degenerate areas, modified Sommerfeld approximation is employed. The simulation of the active layers for polar and nonpolar RTDs are given in Figs.1 and 2, respectively. Conduction and valance bands, Fermi level and electron concentrations are depicted for referral.

3. MATERIAL GROWTH

The RTDs were grown in an AIXTRON 200/4-HT horizontal flow low-pressure MOCVD reactor. Trimethyaluminum and trimethylgallium were used as the metalorganic precursors for Al and Ga, respectively. Silane was used as the n-type dopant source. Ammonia and hydrogen/nitrogen mixture were used as the anion source and carrier gas, respectively.

3.1. Polar Devices

The growth of the polar RTDs started with conditioning of c-GaN substrate followed by 3 μm i-GaN. Along with FS GaN template, we loaded our high quality LEO GaN templates for device regrowth. First, 750-nm-thick n-GaN was grown to act as bottom contact followed by the active layer. Polar RTD active layer employs low aluminium content (20%) in the barrier to prevent the lattice relaxation via dislocation formation as the barrier is grown thinner (1.5 nm) than the critical thickness (~1.8 nm). The RTD active layer, composed of 2.0 nm i-GaN, 1.5 nm i-Al0.20Ga0.80N, 1.25 nm i-GaN, 1.5 nm i-Al0.20Ga0.80N, 20 Å i-GaN, 50 Å n-GaN.

![Figure 1. Schematic, crystallographic directions, and energy band diagram of polar RTD active layer.](image)
i-GaN, 1.5 nm i- Al<sub>0.20</sub>Ga<sub>0.80</sub>N, and 2.0 nm i-GaN, was employed. This arrangement enables a conduction band offset of 0.42 eV in AlGaN barrier, giving a single and discreet electronic level (E) of 0.32 eV in the GaN well. To minimize impurity scattering due to dopant interdiffusion into the barrier regions, thin spacer layers of undoped and reduced doping material is included on either side of the barriers. The device was finalized via top contact layer of 250-nm-thick n-GaN. Figure 1 depicts the polar RTD active layer energy diagram and side view.

### 3.1. Non-polar Devices

Growth of the nonpolar structure started with conditioning of m-GaN substrate followed by 3 μm i-GaN. Then, 400-nm-thick n-GaN was grown to act as bottom contact. The nonpolar RTD active layer was composed of 2.6 nm i-GaN, 1.6 nm i-Al<sub>0.10</sub>Ga<sub>0.90</sub>N, 1.6 nm i-GaN, 1.6 nm i- Al<sub>0.10</sub>Ga<sub>0.90</sub>N, and 2.6 nm i-GaN. This arrangement enables a conduction band offset of 0.16 eV in AlGaN barrier giving a single and discrete electronic level of 0.10 eV in the nonpolar GaN well. To minimize impurity scattering due to dopant interdiffusion into the barrier regions, thin spacer layers of undoped and reduced doping material is included on either side of the barriers. The devices were finalized via top contact layer of 250-nm-thick n-GaN. Figure 2 depicts the nonpolar RTD active layer energy diagram and side view.

![Figure 2. Schematic, crystallographic directions, and energy band diagram of non-polar RTD active layer.](image)

**Figure 2.** Schematic, crystallographic directions, and energy band diagram of non-polar RTD active layer. a, Relative conduction band discontinuities (ΔEc) of RTD active layer and the distribution of electrons are shown. b, Schematic of the RTD active layer with relative layer thicknesses shown along with the crystallographic directions.

### 4. DEVICE FABRICATION

The fabrication was realized via conventional semiconductor methods and tools. It started with the top mesa formation by dry etching (via electron cyclotron resonance reactive ion etching). This was followed by dry etching of excess n-type material (point A in Fig. 3 – where passivation and top metal contact will be deposited later on) This step was to minimize leakage current and parasitic capacitance between contact layers. The bottom contact (points F and G in Fig. 3) composed of 400 Å Ti / 1500 Å Au was deposited via electron beam evaporation. This was followed by 300-nm-thick silicon dioxide passivation layer deposited by plasma-enhanced chemical vapour deposition. This passivation layer was removed from the top contact region of device mesa (i.e. point D in Fig. 3) and bottom contact pads (i.e. point G in Fig. 3) via buffered oxide HF wet-etching. The device was completed by 400 Å Ti / 1500 Å Au top contact metal deposition that formed the top contact bridge to the device mesa and top contact pads.
Figure 3a shows the side-view schematic of the fabricated RTD device. Figure 3b, c shows the top-view optical and scanning electron micrograph (SEM) of the fabricated RTD device. A mesa diameter of 35 µm (Fig. 3b inset) which is connected to the top contact pads via bridge structure (Fig. 3b) is shown. Bottom contact is surrounding the mesa partly to enable efficient carrier injection. In order to better exemplify the fabricated device, letters A through G have been allocated on side-view schematic (Fig. 3a) and top view (Fig. 3b, c).

The transmission line model (TLM) measurements of top and bottom contacts of RTDs grown on polar substrates showed that behaviour of total resistance as a function of TLM contact separation are linear proving top and bottom contacts of polar RTDs ohmic. The specific contact resistances are determined on the order of < 10^{-3} \Omega \cdot cm^2. For the nonpolar substrates, similar TLM measurements of top and bottom contacts were carried out and slightly Schottky contact behaviour (with a barrier height of 1.5 eV) is identified. It is important to note that FS GaN m-plane substrates have the formation of hillocks and TLM patterns by 40 µm x 400 µm contours such hilly areas as well. The ohmicity difference between contacts on polar and nonpolar planes could also be related to different surface energies of polar and nonpolar orientations as the same metal contacts were employed and needs further investigation. The effects of resistivity differences on NDR behavior will be addressed in the electrical measurements.

Figure 3. Typical side-view schematic and top-view images of RTD. a, Side-view schematic of a fabricated RTD device. b, c, Top-view optical (b) and scanning electron micrograph (c) of fabricated RTD device. Inset of (b) shows the SEM bird’s eye view of the mesa. Points A through G shown in the figures correspond to side- (a) and top-views (b, c) of the indicated RTD locations.

5. ELECTRICAL CHARACTERIZATION

All I-V curves were measured using an HP4155A Semiconductor parameter analyzer configured to input a voltage sweep while measuring current. The voltage polarity refers to that applied to the top electrode (see Fig. 3a). For consecutive measurements (Figs. 4 and 5), the voltage sweep was realized consecutively as necessary. No kind of post treatment was realized in-between measurements. I-V measurements were repeated as many to check reliability and confirm reproducibility. All measurements were realized under continuous wave. Low temperature measurements were realized via positioning RTDs inside a liquid N₂ cooled temperature controlled cryostat and carrying out the electrical measurements in a similar manner.

As a bias voltage is applied across the device (the voltage polarity seen in Fig. 3a), the electronic state in the narrower bandgap material (seen in Fig. 1 and 2) is pulled down in energy with respect to the more negative electrode. Electrons from outside the well that hit the barrier structures will largely be reflected, except those within a very narrow range around the discrete energy levels of the well, which acts as an electron energy filter. Thus, the tunneling current through the discrete state depends on the density of occupied states in the electrode as well as how well they are aligned with the discrete electronic level in the well. As shown in the electrical characterization data, when in resonance – energy of the electron states in the electrode align with the discrete energy level of the well – the peak current (I_P) is achieved. This corresponds to the peak voltage (V_P). With further increase in bias, the emitter electron energy level falls below the edge.
of the conduction band into the gap and the current is minimized. In this case, the current and voltage are labelled as valley current ($I_V$) and voltage ($V_V$).

### 5.1. Polar Devices

Aforementioned polar active layer (Fig. 1) was allocated in-between n-GaN contact layers to form the RTD, fabricated as described in the previous section.

Figure 4 shows I-V characteristic of the fabricated polar devices. NDR is clearly observed in both scan directions at NDR voltage onset ($V_P$) of 0.84 V with a stable peak-to-valley current ratio of 1.4. For the experimented polar active layer, the electronic energy level ($E_e$) and Fermi energy level ($E_F$) (reference to conduction band) are calculated as 0.32 eV and 67 meV leading to NDR voltage of ~0.51 V under ideal conditions. The difference between the observed (0.84 V) and ideal $V_{NDR}$ (0.51) is attributed to voltage drop due to the series resistance and polarization charges at the Al$_{0.2}$Ga$_{0.8}$N/GaN interfaces.

The reliability and reproducibility of NDR was studied via tens of I-V scans. The enhanced NDR reproducibility is attributed to (1) very low density of substrate dislocations, (2) low aluminium content in the double barriers, and (3) reduced piezoelectric fields. Lower aluminium content in the barriers not only decreases the lattice-mismatch to GaN and thereby hetero-epitaxial dislocation density, but also lowers the piezoelectric field at the AlGaN/GaN heterointerfaces.

We have looked into the polarity dependence of NDR behaviour. Ideally, as the physical structure is the same, the diode behavior should be symmetric. However, due to the asymmetry of the polarization fields (i.e. 2-D electron gas at AlGaN/GaN interface is only at the GaN side) the reverse bias performance is expected to differ as observed experimentally in Fig. 4 agreeing with the theory. Changing the polarity of the devices, thus, should not change the I-V behavior but only to shift the NDR characteristics (peak voltage/current and valley voltage/current). The lower peak current in the reverse bias is typical in many GaAs-based structures and may arise from out-diffusion of impurities during growth or due to differences in interface roughness between GaN/AlGaN and AlGaN/GaN interface, where the latter is believed to be rougher.

![Figure 4. Electrical characterization of the polar RTDs. (Left) I-V curve of the RTD at room temperature for different scan directions. (Right) I-V curve of the RTD showing NDR for both polarities.](image)

### 5.2. Non-polar Devices

Aforementioned nonpolar active layer (Fig. 2) was allocated in-between n-GaN contact layers to form the RTD, and fabricated as described in the previous section.
Figure 5 shows I-V characteristic of the nonpolar RTD. A clear NDR is observed in the upward scan at 6.6 V. In order to demonstrate the reliability and reproducibility of NDR, tens of I-V scans were taken consecutively without any kind of treatment. The first, thirtieth, and fiftieth scans are plotted in Fig. 5. No significant degradation in the NDR behaviour is observed proving the high material and device quality. The electrical measurements are also taken at cryogenic temperatures and plotted on top of the room temperature characteristics in Fig. 5.

The improvement of the PVR as temperature reduces is related to (1) thermal deactivation of the traps, (2) the decrease in off-resonant current over the barriers due to thermionic emission, (3) the improved confinement of the distribution function around the resonant energy, and (4) reduction in inelastic phonon-assisted tunneling. Lower temperatures improve the NDR behaviour and agrees that this NDR is indeed related to quantum tunneling.34

Typical figures of merit in RTDs are the negative differential resistance (R = 1/\(G_D\)), current peak-to-valley ratio (CPVR = \(I_P / I_V\)) and average oscillator output power (PMAX) (given by \(P_{\text{MAX}} \approx 3/16 \cdot \Delta I \cdot \Delta V\))34. The average values of the R, CPVR and PMAX over fifty-scans are 67 ± 5 Ω, 1.08 ± 0.02 and 0.52 ± 0.01 mW, respectively. These figures of merit, achieved for MOCVD-grown large diameter diodes and at room temperature28, are comparable to the state-of-the-art GaAs-based RTDs4, and demonstrate the promise of III-nitride RTDs for next-generation high power high frequency device applications. The much improved NDR behaviour is attributed to (1) very low density of substrate dislocations, (2) low aluminium content in the double barriers, and (3) elimination of piezoelectric fields28.

6. CONCLUSION

In conclusion, we demonstrate, for the first time, a reliable and reproducible negative differential resistance (R of -67 Ω, CPVR of 1.08 and PMAX of 0.52 mW) in III-nitride RTDs. Our RTDs possess a clear NDR in both reverse and forward bias and improved NDR behaviour at low temperatures. We demonstrate that very low dislocation density and minimization of the polarization charges as the double-barrier hetero-interface are essential to enable reliable and reproducible NDR in GaN-based RTD structures. These works motivate towards further material and device engineering for GaN-based quantum devices. Demonstration of III-nitride RTDs paves the way towards fulfilling the THz gap by two means: via RTD-based electronic oscillators and tunneling-based quantum cascade photonic devices.

REFERENCES