Reliability in room-temperature negative differential resistance characteristics of low-aluminum content AlGaN/GaN double-barrier resonant tunneling diodes

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AlGaN/GaN resonant tunneling diodes (RTDs), consisting of 20% (10%) aluminum-content in double-barrier (DB) active layer, were grown by metal-organic chemical vapor deposition on freestanding polar (c-plane) and nonpolar (m-plane) GaN substrates. RTDs were fabricated into 35-μm-diameter devices for electrical characterization. Lower aluminum content in the DB active layer and minimization of dislocations and polarization fields increased the reliability and reproducibility of room-temperature negative differential resistance (NDR). Polar RTDs showed decaying NDR behavior, whereas nonpolar ones did not significantly. Averaging over 50 measurements, nonpolar RTDs demonstrated a NDR of 67 Ω, a current-peak-to-valley ratio of 1.08, and an average oscillator output power of 0.52 mW. © 2010 American Institute of Physics.

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Resonant tunneling diodes (RTDs) possess a unique quantum-interference characteristic called negative differential resistance (NDR), which is macroscopically identified in device I-V characteristics as the decrease in current with the increase in voltage. NDR, an example of quantum-mechanical tunneling phenomenon in ultrathin structures, is employed in many electronic devices (such as in radios) as well as in the generation and detection of terahertz waves. RTDs, compared to other negative resistance devices such as (Esaki) tunnel and transferred-electron devices (i.e., Gunn diode, Thyristor, and impact ionization avalanche transistors), possess lower junction capacitance (due to relatively lower doping levels), enabling them to operate at higher oscillating frequencies. However, the current bottleneck 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^* ~ 0.2–0.3 × m_0) and longitudinal optical phonon energy (~90 meV) enable ultrafast ISB relaxation offering very high speed devices. Specifically, wide bandgap, large conduction band discontinuity (~2.1 eV in AlN/GaN (Ref. 5)), high carrier mobility, and thermal stability promise high power, high frequency room-temperature operation for GaN RTDs. Demonstrating NDR and understanding the transport in AlGaN/GaN double-barrier (DB) RTDs will enable room-temperature terahertz oscillators and quantum cascade lasers. Despite these promises, there are no reports of reliable NDR in GaN-based DB heterostructures.

Various groups have studied AlN/GaN double-barrier heterostructures grown by molecular beam epitaxy. Recently, we have studied similar structures by metal-organic chemical vapor deposition (MOCVD). In all these works, NDR behavior degraded after the initial electrical measurements. Attempts to increase the reproducibility of NDR included decreasing the template dislocation density, improving active layer quality, and decreasing the device mesa size. However, most of these works were on sapphire substrate that is highly lattice-mismatched to GaN, leading to a high density of dislocations (~10^8 cm^-2). Moreover, these works employed high aluminum content (~70%) barrier designs, leading to large lattice-mismatch at the heterointerfaces. One way to improve the material quality and NDR behavior is by using low-aluminum content AlGaN/GaN double-barrier heterostructures grown on low-dislocated substrates (such as freestanding GaN)—which has not yet been studied.

In this work, we investigate the reliability and reproducibility of NDR in low-aluminum content polar and nonpolar AlGaN/GaN DB RTDs. As such, very low dislocated (~10^5 cm^-2) polar and nonpolar freestanding GaN substrates, and AlGaN/GaN double heterostructures, composed of 20% and 10% aluminum content in barriers, were employed in the active layers of RTDs.

The material was grown in an MOCVD reactor. First, i- and n-GaN carrier concentrations were determined via Hall-effect measurements as ~6 × 10^{16} and ~3 × 10^{19} cm^-3, respectively. Then, the quality, thickness, and aluminum content of the double-barrier active layers were calibrated via AlGaN/GaN superlattice growths followed by x-ray diffraction, photoluminescence, and atomic force microscopy (AFM) studies. After the material calibrations, the growths of RTDs started with 3 μm i-GaN regrowth. Then, 400-nm-thick n-GaN was grown to act as the bottom contact. The DB active layer of RTD is composed of a narrower bandgap material sandwiched between wider bandgap materials; thus, an inherit lattice-mismatch between barrier and well materials is inevitable. The critical thickness (above which dislocations are generated) is inversely proportional to the aluminum content for GaN homoepitaxial growth. Thus, our DB active layer design employs low-aluminum content (20% or 10%) in the barrier to prevent the lattice relaxation via dislocation formation as the barrier is grown.
thinner (1.5 or 1.6 nm) than the critical thickness (∼1.8 or ∼3.0 nm).17 The polar DB active layer was composed of 2.0 nm $i$-GaN, 1.5 nm $i$-$\text{Al}_{0.20}\text{Ga}_{0.80}$N, 1.25 nm $i$-GaN, 1.5 nm $i$-$\text{Al}_{0.20}\text{Ga}_{0.80}$N, and 2.0 nm $i$-GaN, whereas nonpolar RTD active layer was composed of 2.6 nm $i$-GaN, 1.6 nm $i$-$\text{Al}_{0.10}\text{Ga}_{0.90}$N, 1.6 nm $i$-GaN, 1.6 nm $i$-$\text{Al}_{0.10}\text{Ga}_{0.90}$N, and 2.6 nm $i$-GaN. This arrangement enables a conduction band offset of 0.42 (0.16) eV in AlGaN barrier, giving a single and discrete electronic level of 0.32 (0.10) eV in the polar (nonpolar) GaN well. The devices were finalized via top contact layer of 250-nm-thick $n$-GaN [Fig. 2(a)].

The NDR is very sensitive to surface roughness and dislocations and can be observed only for very high material quality.18 A typical (2 μm × 2 μm) AFM scan of the completed polar and nonpolar RTD structure is shown in Figs. 1(a) and 1(b), respectively. The surfaces (a) and (b) possess a root-mean-square roughness of 1.2 and 1.6 Å, respectively. Well-ordered parallel atomic steps are observed in Figs. 1(a) and 1(b) with no dislocation terminations demonstrating the excellent material quality.

Figure 2(a) shows the side-view schematic of the fabricated RTD device. Figures 2(b) and 2(c) show the top-view optical and scanning electron micrograph (SEM) of the fabricated RTD device. The mesa diameter is 35 μm [Fig. 2(b) inset], which is connected to the top contact pads via the bridge structure. The bottom contact is surrounding the mesa partly to enable efficient carrier injection [Figs. 2(b) and 2(c)].

Fabrication of the RTDs was realized via conventional semiconductor methods and tools.12 It started with the top mesa formation by dry etching. This was followed by the dry etching of excess $n$-type material (point A in Fig. 2). This step was to minimize the leakage current and parasitic capacitance between contact layers. Then, the bottom contact (points F and G in Fig. 2) composed of 400 Å Ti/1500 Å Au was deposited. This was followed by the deposition of 300-nm-thick silicon dioxide as passivation. This passivation layer was removed from the top contact region of the device mesa (i.e., point D in Fig. 2) and bottom contact pads (i.e., point G in Fig. 2) via wet etching. The RTD 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.

The transmission line model measurements of the top and bottom contacts of polar and nonpolar RTDs were carried out, and highly Ohmic19 and Schottky contact behaviors (with a barrier height of 1.5 eV) for polar and nonpolar devices were identified, respectively. The ohmicity difference between the contacts on polar and nonpolar planes could be related to the different surface energies of polar and nonpolar orientations as the same metal contacts were employed and need further investigation.

RTD electrical measurements were realized under continuous wave at room-temperature. The voltage polarity refers to that applied to the top electrode [see Fig. 2(a)]. All I-V curves were measured using an HP4155A semiconductor parameter analyzer configured to input a voltage sweep while measuring current.

Figures 3(a)–3(c) show I-V characteristic of the fabricated (a) polar and [(b) and (c)] nonpolar devices. NDR is clearly observed in both devices at NDR voltage onset ($V_p$).
of 2.3 (polar one) and 6.2 V (nonpolar one). The higher $V_p$ of nonpolar device is attributed to contact Schottky barrier.

The reliability and reproducibility of NDR were studied via tens of I-V scans. Figure 3(a) shows the first through 20th scan of the polar device. Although polar Al$_2$Ga$_{0.8}$N/GaN-based device possesses more reproducible NDR than their AlN/GaN-based counterparts, their NDR behavior was observed to suffer from degradation as more scans were carried out. The enhanced NDR reproducibility up to 20 scans is attributed to the lower aluminum content in the double-barriers. Lower aluminum content in the barriers decreases the lattice-mismatch to GaN and thereby dislocation density and lowers piezoelectric field at the AlGaN/GaN heterointerfaces. The lack of reliability—the decrease in NDR voltage and current-peak-to-valley ratio with consecutive scans—is attributed to interface dislocations trapping charges. These trapped charges lower the effective barrier height and alter the dominant transport mechanism. The fact that NDR degrades with increasing scan number suggests that these dislocations do not release the trapped charges and implies further that material improvements are required for more reliable NDR in polar RTDs.

Figures 3(b) and 3(c) plot the I-V curves of nonpolar RTDs. These diodes showed more reproducible and reliable NDR behavior than the polar ones. The first, 30th, and 50th current and voltage are labeled as valley current and voltage. Valley current and voltage are achieved. This corresponds to the peak current ($I_p \approx 83.41$ mA) is achieved. This corresponds to the peak voltage ($V_p \approx 6.24$ V). The expected $V_p$ was $\sim 0.2$ V. The relatively large observed $V_p$ in our device is attributed to the contact Schottky barrier ($\sim 1.5$ V) and the small series resistance that becomes relatively important at high currents ($\sim 80$ mA). These suggest that further improvements in material growth and device fabrication are necessary for ideal performance. 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 labeled as valley current ($I_v \approx 75.36$ mA) and voltage ($V_v \approx 6.62$ V).

Nonpolar devices were further characterized as NDR behavior was reproducible and reliable. For hysteresis measurements [i.e., difference in I-V behavior between upward and downward scan, seen in Fig. 3(c)], the voltage sweep was adjusted for a loop. The hysteresis identified in the I-V curve [Fig. 3(c)] is attributed to charge trapping associated with defects. Defects, charged during the upward scan, broaden the discrete electronic state in the well, preventing the observation of NDR in the downward scan. The fact that these charged defects can be emptied effectively shows that our material and device quality is very high, and the reproducibility of NDR in III-nitride double-barrier heterostructures can be improved by decreasing the aluminum content in the DB active layer, dislocation density, and polarization fields.

Typical figures of merit in NDR devices are the negative differential resistance ($R \approx \Delta V/\Delta I$), current-peak-to-valley ratio (CPVR=$I_p/I_v$), and average oscillator output power ($P_{MAX}$) (given by $P_{MAX}=3/16 \times I_p \times \Delta V$).$^{21}$ The average values of the R, CPVR, and $P_{MAX}$ over 50 scans are $67 \pm 5 \Omega$, $1.08 \pm 0.02$, and $0.52 \pm 0.01$ mW, respectively. These figures of merit, achieved for MOCVD-grown 35-μm-diameter diodes and at room-temperature, are comparable to the state-of-the-art GaAs-based RTDs (Ref. 4) and demonstrate the promise of low-aluminum content nonpolar AlGaN/GaN double-barrier RTDs.

In conclusion, the employment of low dislocation density substrate, polarization-free design, and low-aluminum content active layer approach was shown to increase reliability and reproducibility of NDR in RTDs. GaN-based RTDs possessed an R of $\sim 67 \Omega$, a CPVR of 1.08, and a $P_{MAX}$ of 0.52 mW at room-temperature. Our work motivates further research toward low-aluminum content polarization-free AlGaN/GaN DB-structures grown on low dislocation density substrates.

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