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Investigation of the negative differential resistance reproducibility in AlN/GaN double-barrier resonant tunnelling diodes

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AlN/GaN double-barrier resonant tunnelling diodes were grown by molecular beam epitaxy on GaN/sapphire template and processed into mesa diameters from 2 μm to 4 μm . The current-voltage characteristics were carried out in direct current operation and under-high vacuum. A sharp negative differential resistance (NDR) was detected in the forward bias at 120 K. The NDR was observed for the mesa size of 2 μm at 4 V with a peak-to-valley current ratio of 3.5. The measurement conditions were chosen to make NDR reproducible more than 50 times and apparent in both scan voltage directions after electrical treatment. © 2011 American Institute of Physics.

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Thanks to their negative differential resistance (NDR), resonant tunneling diodes (RTDs) are promising quantum devices for high-speed switching and high-frequency applications. Sub-terahertz RTDs based on GaAs/AlAs and InAs/AlSb structures were demonstrated in the last decade.^{1,2} The implementation of such devices using III-nitride (III-N) semiconductors should make it possible to obtain higher peak-to-valley current ratio (PVR) thanks to their large conduction band offset (1.75 eV).³

III-N materials present high structural defect densities in comparison with conventional III-V semiconductors, which result in leakage current.⁴ The first AlN/GaN double-barrier (DB) RTD was achieved by Kishino *et al.*⁵ However, the NDR was not reproducible in forward bias and was not observed in reverse bias. Since, many other groups have faced the similar difficulties. Indeed, the development of III-N RTDs still remains a challenging task due to the current instability and to the presence of trap-like defects in the heterostructures.⁶ These traps are thermally activated, and therefore, their contribution to the tunneling current is minimized when the temperature decreases,⁷ which should result in a larger PVR. A recent work demonstrated NDR reproducibility in a dislocation-free AlN/GaN nanowires, motivating our study at low temperature.⁸

The aim of this work is to investigate the electronic transport through AlN/GaN RTDs at low temperature, with the purpose to obtain the current-voltage (I-V) characteristic when traps are frozen in their filled state. For this purpose, we chose a top-bottom approach keeping the AlN barriers below the critical thickness on GaN.⁹ The heterostructure consists of a 1 nm thick AlN double-barrier, with a 1 nm thick GaN quantum well, embedded in an n-GaN matrix. The sample is grown by plasma-assisted molecular beam epitaxy on a 10 μm thick GaN-on-sapphire template. A 250 nm thick n-GaN layer is first deposited on the template to improve the bottom ohmic contact and reduce the access resistance. The Si-doping of the n-GaN layer is estimated to

$5 \times 10^{19} \text{cm}^{-3}$. In order to avoid Si diffusion into the barriers, 1 nm i-GaN spacers are grown before and after the AlN/GaN/AlN DB structure. On top of the active area, a 200 nm thick n-GaN cap layer is deposited (Fig. 1(a)). The dislocations density is estimated to $6 \times 10^8 \text{cm}^{-2}$.

The number of dislocations per mesa can be reduced by down scaling the RTDs. In this work, mesas with 2 μm , 3 μm , and 4 μm diameter were fabricated using microelectronic processing techniques. First, a 150 nm thick silicon nitride (Si_3N_4) mask was deposited by plasma-enhanced chemical vapor. Next, the RTDs mesas were defined by lithography and patterned in two steps of dry-etching: first the Si_3N_4 mask etching using CH_4 -based reactive-ion-etching (RIE) and second the etching of the active region corresponding to mesa using Cl_2 -based inductive-coupled-plasma RIE. After removal of the Si_3N_4 mask, a Ti/Al/Ni/Au multilayer was deposited by electron-beam evaporation followed by lift-off and a rapid-thermal-annealing at 750 °C, to form the bottom Ohmic contact.

The electrical characterization of the RTDs was performed in ultra-high vacuum with an Omicron Nanoprobe (Fig. 1(b)). The bottom Ohmic contact is connected to the ground via a macro-pad linked to the sample holder. The voltage bias is applied by the tungsten nano-tip which is connected to the top diode. This electrode acts as a rectifier contact, so the NDR can only be observed in forward bias (Fig. 2(b)). Electrons are injected from the substrate side to the top electrode for forward bias and from the top electrode to the substrate in reverse bias.

At room temperature, the I-V characteristic of the diodes does not exhibit NDR but sometimes a resonance peak is observed followed by current instabilities. In contrast, at 120 K, a well-resolved NDR is observed for diodes with a diameter smaller than 4 μm . When scanning from zero bias to a positive voltage, the I-V characteristics exhibits a resonance peak at the first measurement that disappears in the following measurements. The diode of 2 μm shows a PVR of about 3.5 (Fig. 2(a)), whereas the diode of 3 μm shows a PVR around 2.5 (Fig. 3(b)). The current hysteresis is related to charge trapping associated to structural defects, particularly treadng

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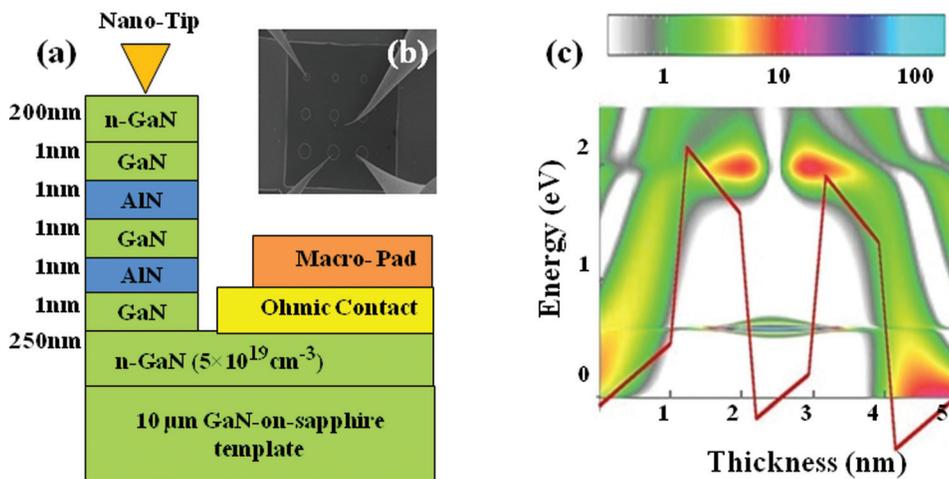


FIG. 1. (Color) (a) Schematic view of the investigated RTD heterostructure; (b) SEM top view of the fabricated RTDs mesa; (c) the conduction band profile and the electrons density of states of the RTD at 0 V bias.

dislocations. In agreement with previous reports, the NDR appears only under the forward bias and disappears in the backward scan. This behavior could be related to the activation of electron traps due to the high voltage applied to the structure.⁷

The simulated electron density of states for the investigated AlN/GaN DB-RTD was calculated using the non-equilibrium Green's functions (Fig. 1(c)). The internal fields produced by spontaneous and piezoelectric polarization lead to the formation of a two dimensional electron gas and depletion region near the AlN/GaN interfaces, in the side of the cathode and anode, respectively. The expected peak voltage (V_{NDR}) should appear at ≈ 1.1 V. The relatively large differences between the predicted and the measured V_{NDR} in our devices are attributed to the series resistance and to self-heating due to the power dissipation at high current density.^{10,11}

Thanks to the rectifier contact, important features are revealed after applying a negative voltage of -6 V during 1 min. Subject to this treatment, the $2 \mu\text{m}$ RTD exhibits NDR in both scan directions at around 3.7 – 3.9 V (Fig. 4(b)). In the case of the $3 \mu\text{m}$ RTD, the NDR is not apparent in the back-

ward scan. For both diameters, the measurement is not reproducible on the consecutive scans. In fact, the electric field, in the high-field regions and particularly in AlN barriers, strongly changes the trap energy level and the curvature of the triangular barriers band bending. This behavior permits to empty efficiently the traps by tunneling effect assisted by field effect (Poole-Frenkel effect).⁷

In view of the curing effect of reverse bias, we have analyzed the effect of scanning the voltage from negative to positive bias. The measurements show a remarkable improvement in the stability of the NDR. Under these conditions, the NDR is reproducible more than 50 scans for the $2 \mu\text{m}$ diodes and more than 20 times for the $3 \mu\text{m}$ diodes (Figs. 3(a) and 4(a)). These results are in agreement with previous reports, which reported a bistable behavior in RTD structures requiring negative bias to observe NDR.¹² Such reproducibility can be explained by the traps discharging located in the barriers under sufficient electric field. During consecutive measurements, the peak voltage shifts to lower voltage followed by current instabilities in the backward scan, as observed by other groups.^{13,14} This behavior can be qualitatively explained by the accumulation of charge in

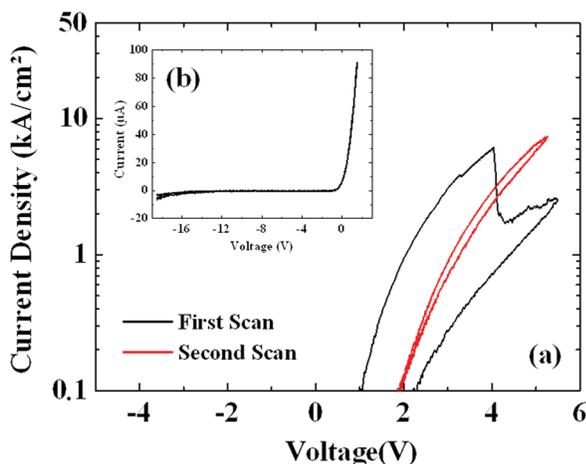


FIG. 2. (Color) (a) The current-voltage characteristics of the $2 \mu\text{m}$ diameter RTD measured at 120 K without electrical treatment, the voltage is scanned from 0 V to a positive voltage; (b) the current-voltage curve measurement of the rectifier contact on the top of the RTD at 120 K.

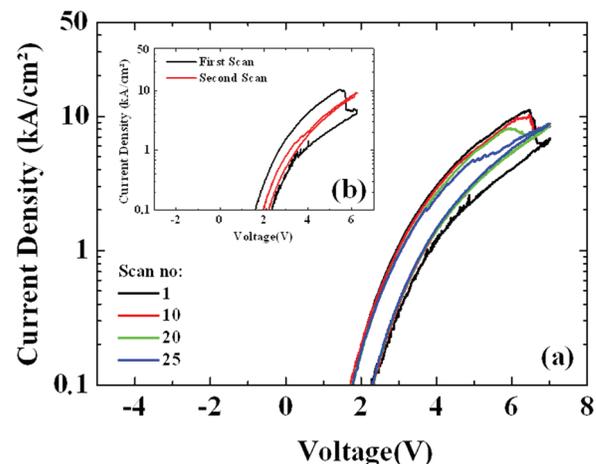


FIG. 3. (Color) The current-voltage characteristics of the $3 \mu\text{m}$ diameter RTD measured at 120 K without electrical treatment; (a) the voltage is scanned from -19 V to a positive voltage; inset (b): the voltage is scanned from 0 V to a positive voltage.

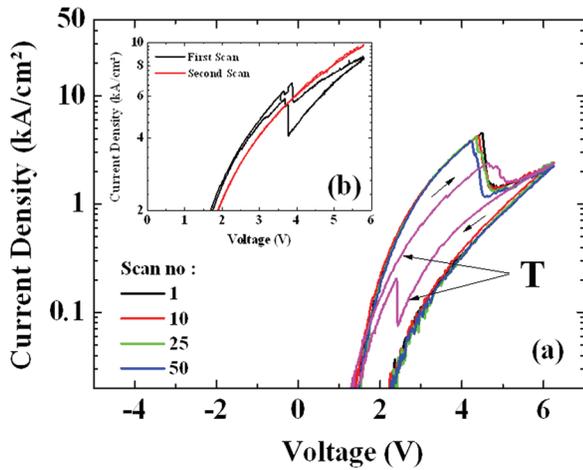


FIG. 4. (Color) The current-voltage characteristics at 120 K for the $2\ \mu\text{m}$ RTD without electrical treatment; (a) the voltage is scanned from $-13\ \text{V}$ to a positive voltage; (b) the voltage is scanned from $0\ \text{V}$ to a positive voltage; inset (T) with electrical treatment.

traps located in the near-barrier region, which masks the quantum level and hence shifts V_{NDR} . The NDR slowly decays after repeated measurements for the $2\ \mu\text{m}$ diode. This behavior is more pronounced for the $3\ \mu\text{m}$ diode, where the peak current decreases while the valley current increases. This feature suggests that trapped charges are released only partially under application of reverse bias.

After electrical treatment, the diode of $2\ \mu\text{m}$ exhibits a NDR in both scan directions at $4.2\ \text{V}$ - $2.2\ \text{V}$, as previously (inset T of Fig. 4). In the backward scan, the peak voltage shifts to lower voltage and the peak current drastically decays. In the following measurements, the resonance peak totally disappears. This behavior is ascribed to the electric field distribution in the structure and to the kinetic of (de)trapping under high-bias voltage.

In summary, we have demonstrated that the NDR can appear in both scan directions after electrical treatment. The NDR reproducibility can be drastically improved when scanning the voltage from a sufficient negative starting point bias. We have also shown that the rectifier contact on the top electrode is responsible of detrapped charges by Poole-Frenkel effect in DB-RTDs. Furthermore, the I-V characteristics are very sensitive to the mesa size. These promising results constitute a motivation in the future for the fabrication of nano-diodes.

¹E. R. Brown, T. C. L. G. Sollner, C. D. Parker, W. D. Goodhue, and C. L. Chen, *Appl. Phys. Lett.* **55**, 1777 (1989).

²E. R. Brown, J. R. Soderstrom, C. D. Parker, L. J. Mahoney, and K. M. Molvar, *Appl. Phys. Lett.* **58**, 2291 (1991).

³S. Sakr, E. Warde, M. Tcherycheva, and F. H. Julien, *J. Appl. Phys.* **109**, 23717 (2011).

⁴J. W. P. Hsu, M. J. Manfra, R. J. Molnar, B. Heying, and J. S. Speck, *Appl. Phys. Lett.* **81**, 79 (2002).

⁵A. Kikuchi, R. Bannai, and K. Kishino, *Phys. Status Solidi A* **188**, 187 (2001).

⁶A. M. Kurakin, S. A. Vitusevich, S. V. Danylyuk, A. V. Naumov, C. T. Foxon, S. V. Novikov, N. Klein, H. Lüth, and A. E. Belyaev, *Phys. Status Solidi C* **3**, 2265 (2006).

⁷M. V. Petrychuk, A. E. Belyaev, A. M. Kurakin, S. V. Danylyuk, N. Klein, and S. A. Vitusevicha, *Appl. Phys. Lett.* **91**, 222112 (2007).

⁸R. Songmuang, G. Katsaros, E. Monroy, P. Spathis, C. Bougeral, M. Mongillo, and S. De Franceschi, *Nano Lett.* **10**, 3545 (2010).

⁹A. D. Bykhovskii, B. L. Gelmont, and M. S. Shur, *J. Appl. Phys.* **81**, 6332 (1997).

¹⁰C. Bayram, Z. Vashaei, and M. Razeghi, *Appl. Phys. Lett.* **96**, 042103 (2010).

¹¹S. Golka, C. Pflügl, W. Schrenk, G. Strasser, C. Skierbiszewski, M. Siekacz, I. Grzegory, and S. Porowski, *Appl. Phys. Lett.* **88**, 172106 (2006).

¹²A. E. Belyaev, C. T. Foxon, S. V. Novikov, O. Makarovskiy, L. Eaves, M. J. Kappers, and C. J. Humphreys, *Appl. Phys. Lett.* **83**, 3627 (2003).

¹³C. T. Foxon, S. V. Novikov, A. E. Belyaev, L. X. Zhao, O. Makarovskiy, D. J. Walker, L. Eaves, R. I. Dykeman, S. V. Danylyuk, S. A. Vitusevich, M. J. Kappers, J. S. Barnard, and C. J. Humphreys, *Phys. Status Solidi C* **0**, 2389 (2003).

¹⁴C. Bayram, Z. Vashaei, and M. Razeghi, *Appl. Phys. Lett.* **97**, 181109 (2010).