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Mechanisms of current formation in resonant tunneling AlN/GaN heterostructures

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This paper presents an analysis of transport and noise properties of double-barrier resonant tunneling diodes formed on the basis of AlN/GaN heterostructures. Two stable states are registered in the *I-V* characteristics of the diodes. The temperature dependences of current and noise behavior are analyzed to understand the contribution of different mechanisms responsible for current formation in the structures. The evolution of the spectral density of the noise current with temperature reveals several recombination-generation components. The mechanisms responsible for the formation of current in AlN/GaN/AlN diodes are discussed taking into account the Poole-Frenkel effect. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2817752]

Double-barrier resonant tunneling diodes (RTDs) are known as unique quantum-mechanical devices allowing negative differential resistance effects to be utilized at room temperature. Thin-barrier RTDs are especially promising for high frequency (up to terahertz) generation due to their extremely high-speed transport properties with characteristic times in the order of a few picoseconds.[1–3] Moreover, subterahertz frequency generation based on GaAs/AlAs heterostructures was recently demonstrated at 420 GHz (Ref. 4) and at 712 GHz in the case of InAs/AlSb heteropairs.[5] The main drawback of these oscillators is a limited output power in the order of few microwatts. In the last few years, researchers have devoted considerable efforts to develop high-power RTD generators using GaN-based materials.[6] A combination of wide band gap and high carrier mobility to sustain high voltages and currents simultaneously will allow an increase of output power that is necessary for broader area applications of high-frequency RTDs. Another unique property of GaN-based heterostructures is a large band offset that can result in additional emitter sources for quantum-mechanical tunneling processes,[7] which significantly expand the functionality of RTDs. The RTD structures based on AlN/GaN were demonstrated by Kashino and Kikuchi.[8] It should be noted that GaN-based RTDs still exhibit instabilities.[9] Recently, *C-V* characteristics of the structures[10] measured at increased frequencies reveal a reproducible minimum of capacitance at a voltage, which is in good agreement with the simulated maximum of resonant tunneling current in the RTD structures. In this work, we present results of investigations on the mechanisms of current formation in GaN-based RTDs using the method of low-frequency noise spectroscopy. Two stable states of operation of RTDs were discovered and analyzed in a model that takes into account the peculiarities of charge transport through the structure in the presence of traps.

GaN-based heterostructures were grown at 800 °C by molecular beam epitaxy on 5 μm thick undoped metal-organic chemical-vapor deposition–GaN templates realized on sapphire substrates. The active part of the device consists of a 2 nm AlN barrier layer, a 2 nm GaN quantum well, and a 1 nm AlN barrier layer followed by a 300 nm GaN top layer. RTD devices with different diameters (from 5 to 800 μm) were fabricated using a reactive ion etching technique. Ti–Al metallization layers were deposited to form Ohmic contact with top and bottom layers.

The *I-V* characteristics were measured in the dc regime within a temperature range $T=70-300$ K using a Stirling cooler. Spectral noise measurements were performed simultaneously in the frequency range from 1 Hz to 100 KHz using a low noise preamplifier and spectrum analyzer HP 35670A.

I-V characteristics of the RTDs were measured in cycles from negative to positive polarity and back by gradually increasing the applied voltage. Positive voltage bias corresponds to the polarity at which the electrons are emitted from the substrate side, and negative bias to the polarity at which electrons are injected from the top contact side. The RTD structures exhibit a resonance peak in the *I-V* characteristics at negative bias, but the peak current decreased in subsequent *I-V* measurements, and after several runs, the peak disappeared, as was previously registered in RTDs.[10] Important features were revealed after increasing the applied voltage to 6 V for 20 min [both positive (T^+) and negative (T^-) polarity] while maintaining the dissipated power in the order of 0.5–0.6 W. The sample demonstrates two stable states in the low-voltage *I-V* characteristics of the diode. Typical *I-V* characteristics for two registered stable states after the 6 V bias was applied are shown in Fig. 1(a). It can be seen that after (T^+) treatment, the *I-V* characteristic shifted to lower currents in comparison to the effect registered after the (T^-)

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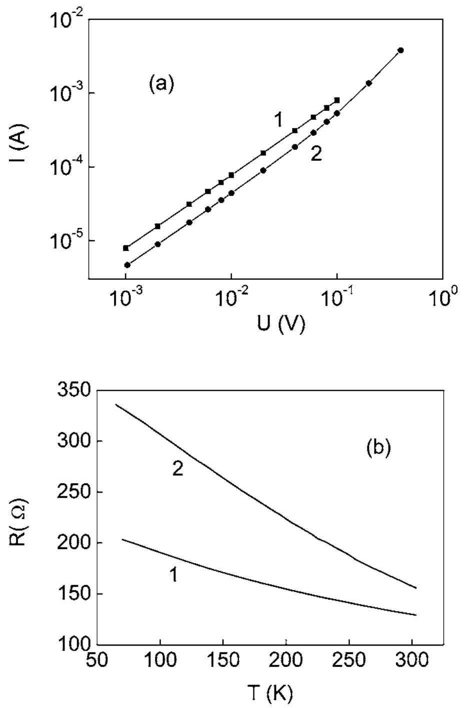

FIG. 1. (a) *I-V* characteristics of the RTD structure measured under negative bias with respect to grounded substrate: curve 1 is measured after the (T^-) treatment and curve 2 after (T^+). (b) Dependence of resistance of the structure on temperature: curve 1 is measured after the (T^-) at $U=-60$ mV and curve 2 after (T^+) at $U=-60$ mV.

regime. The temperature dependence of the sample resistance under low-voltage (below 0.1 V region) conditions [Fig. 1(b)] was found to be close to exponential behavior. The resistance increases more slowly after (T^-) treatment than after (T^+) with decreasing temperature. Taking into account the fact that the tunneling current has a weak temperature dependence, it is evident that in the (T^-) case a contribution of tunneling electrons to total current is higher than that for the (T^+) treatment.

The tunneling component of the current strongly depends on the height of the potential barrier. Therefore, the two stable states after each of the treatment regimes are reflected in the different values of the potential barrier. After the (T^+) treatment, the height of the potential barrier increases and after (T^-), it decreases.

The temperature dependence of the noise spectra characteristics was investigated to analyze the mechanisms of current flow and trap parameters in the structure. Noise spectra were measured in a linear regime of the *I-V* characteristic at a voltage $U=-60$ mV. The investigated spectra demonstrate both $1/f$ noise and generation-recombination (GR) noise components. The $1/f$ component dominated in the temperature range around 300 K, where the noise level has practically the same level after the +6 and −6 V treatments. At a lower temperature range, the $1/f$ noise level decreases, even more strongly after the (T^-) treatment than after the (T^+) treatment. Additionally, a number of GR components were registered at different temperatures at reduced $1/f$ noise level. It is convenient to analyze the temperature dependence of noise spectra representing them as isolines, describing noise levels at a fixed frequency. Such a dependence of normalized noise at frequency $f=3$ Hz after the (T^-) and (T^+) treatments is shown in Fig. 2.

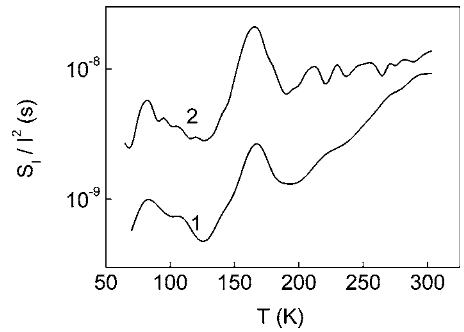

FIG. 2. Temperature dependences of normalized current noise measured at frequency $f=3$ Hz and $U=-60$ mV after the (T^-) treatment (curve 1) and after (T^+) (curve 2).

An analysis of the temperature dependences allowed us to estimate the activation energies of the traps responsible for GR noise components (Fig. 3). After the (T^+) treatment, six separate GR noise components were revealed with energies of 0.66, 0.52, 0.43, 0.23, 0.20, and 0.13 eV. In contrast, after the (T^-) treatment regime, only the first three levels can be resolved, but instead of the last three traps, two new levels appear with energies of 0.16 and 0.08 eV. Most likely these are the same states as in the case of the (T^+) regime, namely, 0.23 and 0.13 eV traps, but with energy levels reduced by 0.07 and 0.05 eV, respectively. As it will be shown below, such a reduction can be explained by a strong redistribution of electric fields in the structure.

The questions about the field distributions and GR center positions can be solved by the analysis of the potential profiles of the structure at different applied voltages. The profiles were calculated by self-consistently solving the Schrödinger and Poisson equations, taking into account the polarization effects in the structure (Fig. 4). The active part of the structure consists of two AlN barriers and a GaN quantum well in between. The depleted space-charge region is adjacent to the double barrier part. It is known that the modulation noise of high Ohmic regions in diodes is much higher than the noise of neutral regions.[11] Therefore, taking into account the rather high level of measured noise and the relatively low resistance of the structures, the main source of noise is considered to be positioned inside the potential barriers. The noise registered is caused by charge fluctuations due to the modulation of width and height of the barriers. In the temperature range above 200 K (curve 1 in Fig. 2) 260 K (curve 2 in Fig. 2), the noise exhibits $1/f$ behavior typical for

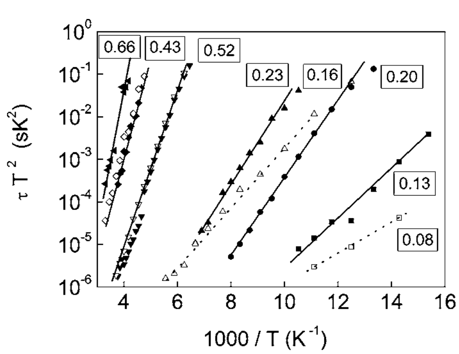

FIG. 3. Temperature dependences of time constants of GR noise components multiplied by the square of temperature (Arrenius plot) after the (T^+) procedure (filled circles) and after (T^-) (open circles), $U=-60$ mV. The numbers on the plots are the estimated trap activation energies in eV.

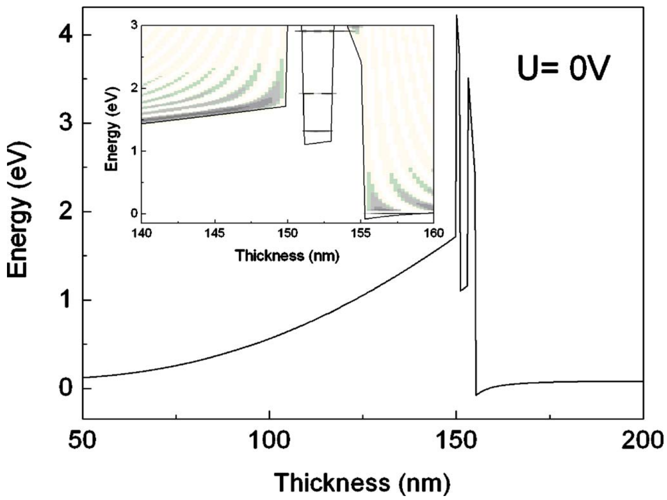

FIG. 4. (Color online) Self-consistently calculated conduction band profile and electron density of states for the investigated AlN/GaN RTD at 0 V bias.

flicker noise. The temperature dependence of the flicker noise for the above-mentioned temperature range extracted from Fig. 2 in the form of $S_I^{1/f} \sim \exp(\gamma T)$, is typical for the tunneling-recombination mechanism of current formation.[11] Therefore, in our case, a tunneling-recombination current is an essential component of the total current, and the level of the corresponding $1/f$ noise is practically of the same order of magnitude for both (T^{+}) and (T^{-}) treatments in the temperature range above 260 K.

In the low temperature range, the GR noise components are registered, where the flicker noise component is considerably lower than that for the temperature range near $T=300$ K. Noise traps in our structure (Fig. 3) can be divided into two groups—that dependent on treatment-type (T^{+}) and (T^{-}) and that independent of it. The latter group of traps is located in the depleted low-field space-charge region of the device, while the first group is in the high-field region, where strong field dependence on charge distribution results in the metastable character of the states. The electric field in the high-field regions—in our case in AlN barriers—strongly changes the energy level of the traps. Therefore, the activation energies of the first group of centers can be used as an indicator of strength of the electric field. The change of the activation energy with field can also be calculated using the band-banding effect in the high electric field (the Poole-Frenkel effect). Since the total current is lower after the (T^{+}) treatment than after the (T^{-}), the potential barriers are therefore higher for the (T^{+}) case. In this case, we obtained a lowering of the activation energies of GR centers, which is in good agreement with our model. For a quantitative analysis, we estimated the electric field strength that is necessary to obtain the registered shift in trap's activation energies using the equation

$$\exp\left[\frac{\beta}{kT}(\sqrt{E+\Delta E}-\sqrt{E})\right]=\exp\frac{e\Delta U}{kT}, \qquad (1)$$

where E is the electric field strength near the trap center, ΔE is the change of the electric field strength, ΔU is the hypothetical change of the activation energy of a level under equilibrium conditions, k is the Boltzmann constant, T is the temperature, e is the electron charge, $\beta=(e^3/\pi\varepsilon\varepsilon_0)^{1/2}$, ε is the relative dielectric constant, and ε_0 is the vacuum permittivity.

The left side of Eq. (1) corresponds to a change of current through the structure caused by the Poole-Frenkel effect. The right side of Eq. (1) reflects a similar change in a current, caused by a hypothetical change in the activation energy of a trap level under equilibrium conditions.

The solution of the Eq. (1), taking into account the fact that the electric field value in the barrier region is approximately equal to $E=2\times10^6$ V/cm, gives us the ΔE value of the electrical field change of $\Delta E=(7-10)\times 10^5$ V/cm, which results in a change in the observed level energy for the registered value of $\Delta U=0.05-0.07$ eV. It can be seen that the value obtained is about two to three times lower than the value of the electric field in the barrier. This fact is an additional confirmation that the Poole-Frenkel effect describes very well the registered changes in the activation energy of the local centers.

In conclusion, two stable states of current formation in the RTD structure were revealed. Transport and low frequency noise spectra measurements allowed us to analyze the mechanisms of current formation in the RTD structures. Two types of GR noise centers in the structure are registered. The first group of traps is independent of high-voltage treatment conditions while the second group of traps changes their energy position depending on the polarity of the high-voltage treatment. The stable centers are found to be in the depleted low-field space-charge region of the device, while the second type of traps are located in the high-field region, where the field results in the change of metastable states of the traps in the AlN barrier layer. The instability of current in the *I-V* characteristics of the RTD devices is caused by a redistribution of potential in the structure, which is stronger in the barrier region. The latter phenomenon leads to the observed change in activation energy of the traps located in AlN layers.

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