Electron transport through cubic InGaN/AlGaN resonant tunneling diodes

N. Yahyaoui a,⁎, N. Sfina a, S. Abdi-Ben Nasrallah a, J.-L. Lazzari b, M. Said a

a Laboratoire de la Matière Condensée et des Nanosciences (LMCN), Département de Physique, Faculté des Sciences de Monastir, Avenue de l’Environnement, 5019 Monastir, Tunisia
b Centre Interdisciplinaire de Nanoscience de Marseille (CINaM), UPR CNRS 3118 associée à Aix-Marseille Université, Case 913, Campus de Luminy, 13288 Marseille cedex 9, France

ARTICLE INFO

Article history:
Received 16 April 2014
Received in revised form 5 August 2014
Accepted 9 August 2014
Available online 20 August 2014

Keywords:
Cubic nitride
Resonant tunneling diode
Electron transport

ABSTRACT

We theoretically study the electron transport through a resonant tunneling diode (RTD) based on strained AlxGa1−xN/InyGa1−yN/AlxGa1−xN quantum wells embedded in relaxed n-Al0.15Ga0.85N/strained In0.1Ga0.9N emitter and collector. The aluminum composition in both injector and collector contacts is taken relatively weak; this does not preclude achieving a wide band offset at the border of the pre-confinement wells. The epilayers are assumed with a cubic crystal structure to reduce spontaneous and piezoelectric polarization effects. The resonant tunneling and the thermally activated transfer through the barriers are the two mechanisms of transport taken into account in the calculations based on the Schrödinger, Poisson and kinetic equations resolved self-consistently. Using the transfer matrix formalism, we have analyzed the influence of the double barrier height on the resonant current. With an Al composition in the barriers varying between 30% and 50%, we have found that resonant tunneling dominates over the transport mediated by the thermally activated charge transfer for low applied voltages. It is also found that the designed n-type InGaN/AlGaN RTD with 30% of Al composition in the barriers is a potential candidate for achieving a resonant tunneling diode.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

During the last decade, GaN/Al(In, Ga)N heterostructures have received much attention in the nanoelectronics and nanophotonics research communities. It is worth noting that conduction band offsets in the InyGa1−yN/AlxGa1−xN cubic system is much larger than those of the InyAs/AlxAs cubic system. Owing to their outstanding properties such as wide direct bandgap, large band offset, high peak electron velocity, high saturation electron velocity and high thermal stability [1–4], III-nitrides are excellent candidates for instance the fabrication of high temperature THz quantum cascade lasers [5,6] or Resonant Tunneling Diode (RTD) with expected high Negative Differential Resistance (NDR) and current peak to valley ratio (PVR) for high power device applications. However, if large NDR observed at Room Temperature in Al(Ga)N/GaN diodes has been assigned to resonant tunneling [7], they are sensitive to the internal electric field present in wurtzite III-nitride compounds and to the piezoelectric effect [8]. All these applications require the study of vertical transport using basically the double-barrier (DB) formed by cubic nitrides, like for conventional AlGaaS /InGaAs RTDs. Resonant tunneling through DB structures did not only represent one of the most interesting phenomena in quantum mechanics but are also very important for the current transport through heterostructures or superlattices. Resonant tunneling diodes are unique quantum devices allowing negative differential resistance (NDR) to be recognized at room temperature (RT) [9]. They have been made in a variety of material systems, including (AlGa)AlAs [10], Si/Ge [11] and InAs/GaSb [12]. A resonant tunneling has been successfully shown in the hexagonal group III-nitrides [13,14]. All available commercially group III-nitride-based optoelectronic devices are grown along the polar c direction of the hexagonal (wurtzite) crystal. In these structures, spontaneous and piezoelectric polarizations induce electric fields in the structure that are perpendicular to the growth direction, resulting in tilted energy bands [15]. These built-in fields are undesirable for optical devices like...
Fig. 1. The conduction band profile along the strained n-Al$_{0.15}$Ga$_{0.85}$N/In$_{0.1}$Ga$_{0.9}$N/Al$_{0.1}$Ga$_{0.9}$N structure with the values of the conduction band edges respectively ($\Delta E_c = 0.441$ eV, $\Delta E_c = 0.605$ eV and $\Delta E_c = 0.812$ eV).

quantum well infrared photodetectors (QWIP) or quantum cascade laser (QCL) [16]. In fact, electric fields spatially separate the electron and hole wave functions in the quantum wells (QWs), limiting the optical efficiency of c-plane devices [17]. Moreover, the Quantum–Confined Stark Effect causes a decrease of the emission peak wavelength (blue-shift of the emission energy) by increasing the driving current. This inherent polarization limits the performance of optoelectronic devices containing quantum well or quantum dot active regions. To get rid of this problem much attention has been focused on the growth of non- or semi-polar (Al, Ga, In)N. Growth of the meta-stable cubic phase of GaN (c-GaN) and AlN (c-AlN) is a possibility to avoid these built-in fields, because of the cubic crystal symmetry [18]. Cubic group III-nitrides offer large potential for intersubband devices due to their large band offsets [19] and non-polarity. During the last decades, a great progress in the fabrication of cubic III-nitride intersubband devices was made. Machhadani et al. [20] showed intersubband absorption of cubic in the near infrared to terahertz spectral range. Recently, Zainal et al. [21] have demonstrated that the resonant tunneling through cubic GaN/AlGaN double barriers on GaAs provides numerous interesting phenomena. The GaN-based RTD heterojunctions are characterized by a much larger conduction band discontinuity [22] than in the GaAs-based RTD system. These properties have significant effects on the electronic transport in quantum devices. However, if large NDR observed at Room Temperature in Al(Ga)N/GaN diodes has been assigned to resonant tunneling [23], they are sensitive to the internal electric field present in wurtzite III-nitride compounds and to the piezoelectric effect [22]. All these applications require the study of vertical transport using basically the double-barrier (DB) formed by cubic nitrides, like for conventional AlGaAs/InGaAs RTDs. In this work, we have theoretically studied the electronic transport mechanisms through the resonant tunneling diodes based on cubic InGaN/AlGaN. Then, transmission coefficients, resonant tunneling and thermally activated current densities for the considered system are investigated using the transfer matrix method. This model describes the electron transport by considering the influence of the conduction band offsets.

2. Theoretical calculation

Our modeled RTD consists of three InGaN quantum wells (QWs) between two Al (Ga)N barriers where the Al content varies between 30% and 50%; the whole is surrounded by doped AlGaN layers. Thus, we propose a carrier transport model of n-type InGaN/AlGaN RTDs in which external n-Al$_{0.15}$Ga$_{0.85}$N/In$_{0.1}$Ga$_{0.9}$N and In$_{0.1}$Ga$_{0.9}$N/Al$_{0.15}$Ga$_{0.85}$N regions act as electron injector and collector for internal Al$_{0.1}$Ga$_{0.9}$N/In$_{0.1}$Ga$_{0.9}$N/Al$_{0.1}$Ga$_{0.9}$N quantum wells. The conduction band profile at zero bias is schematically shown in Fig. 1. Our calculations are based on the resolution of the Schrödinger, Poisson and kinetic equations self-consistently.

In the one band version of the envelope function approximation, the quantized energy levels $E_i$ and their corresponding wave functions $\psi_i$ are obtained by solving the one-dimensional Schrödinger equation in the growth direction $z$ [24]:

$$-rac{\hbar^2}{2m_e} \frac{\partial}{\partial z} \left( \frac{1}{m_e} \frac{\partial}{\partial z} \right) \psi_i(z) + V(z) \psi_i(z) = E_i \psi_i(z)$$

(1)

where $\hbar$ is the reduced Plank’s constant; $m_e(z)$ is the electron effective mass in the conduction band along the $z$ direction. The potential $V(z)$ includes the band diagram discontinuities at interfaces between layers $V_0(z)$ and the Hartree term due to the electrostatic potential energy $\phi(z)$. The Hartree potential is obtained by solving Poisson’s equation [25]:

$$\frac{\partial}{\partial z} (\varepsilon(z) \frac{\partial}{\partial z} \phi(z)) = \frac{q[N_D(z) - n(z)]}{\varepsilon_0}$$

(2)

where $q$ is the electronic charge, $\varepsilon_r(z)$ is the dielectric constant, $\varepsilon_0$ is the vacuum permittivity, $N_D$ refers to the ionized donor doping concentration and $n(z)$ is the free electron concentration. This free-carrier concentration is obtained by the following equation:

$$n(z) = \frac{m^* k_B}{\pi \hbar^2} \sum_{ie} \ln \left[ 1 + \exp \left( \frac{E_F - E_{ie}}{k_B T} \right) \right] \left| \psi_{ie}(z) \right|^2$$

(3)

with $E_{ie}$ is the eigenvalue for electrons and $E_F$ refers to the Fermi level which is determined by solving numerically the electro-neutrality equation.
Furthermore, the transport model has taken into consideration the thermally activated electron transfer through the InGaN/AlGaN RTD structure. To analyze the thermally activated carrier transport, the electron transfer components in two opposite directions from the confinement regions are included. This carrier transport is described by kinetic equations.

The electron concentration rate $n_i$ in the $i$th quantum well mesh point is given by [26]:

$$\frac{dn_i}{dt} = g_{i-1\rightarrow i}n_{i-1} - n_i g_{i\rightarrow i+1} - n_i g_{i\rightarrow i-1} + n_{i+1} g_{i+1\rightarrow i}$$

(4)

where $n_i$ is the electron concentration in the $i$th mesh point ($i = 1, \ldots, N$, where $N$ is the number of mesh points); $g_{i\rightarrow i+1}$ and $g_{i+1\rightarrow i}$ are the carrier transfer rate from $i$ to $i+1$ mesh point and in the opposite direction. This rate, defined within the thermally activated transport theory, includes the image-force effect in the following way [26,27]:

$$g_{i\rightarrow i+1} = \omega_0 \exp\left(\frac{q(\phi_i - \phi_{i+1})}{k_B T}\right) \exp\left(-\frac{\Delta E_{\xi i}}{k_B T} - \frac{q^2(\phi_i - \phi_{i+1})}{16\pi \varepsilon_0 \hbar z_i}\right)$$

(5)

where $z_i$ is the mesh step, and $\omega_0$ is the local carrier oscillation frequency in the quantum well ($\omega_0 = 10^{12}$ s$^{-1}$ [28]). All variables $\phi(z)$, $\Delta E_{\xi}(z)$ and $\varepsilon(z)$ have been attached to discrete mesh.

The potential $V(z)$ and the Fermi level $E_F$ serve to determine the transmittance probability of carriers $T$ in order to assess the tunneling current. The calculation of the current through the RTD structure is evaluated based on the transfer matrix formalism. Besides the high computational efficiency of this approach, this method is well adapted for our case. So, when the wave-function of the carrier is obtained, the calculation of the current through the RTD structure is evaluated based on the transfer matrix formalism.

The potential $V(z)$ and the Fermi level $E_F$ may be defined from the wave function continuity $\psi(z)$ and its derivative divided by the corresponding effective mass. In our case, the energy profile $V(z)$ is broken down into $N + 1$ flat potential segments between two points, $z_0$ and $z_N$, so that the solutions are plane waves:

$$\psi(z) = A_i \exp(i k_i z_i) + B_i \exp(-i k_i z_i)$$

(6)

where $A_i$ and $B_i$ are the transmitted and reflected amplitudes respectively while $k_i$ is the wave vector in the segment $i$. Hence, the transfer matrix between two consecutive segments $i$ and $i + 1$ can be written as:

$$\begin{bmatrix}1 + \frac{m_{i+1}}{m_i} & k_i \\ 1 - \frac{m_{i+1}}{m_i} & k_i \end{bmatrix} \exp i(k_i k_{i+1}) \begin{bmatrix}1 & k_i \\ 1 & k_i \end{bmatrix} \exp -i(k_i k_{i+1})$$

(7)

and the electron transmission coefficient, defined as the ratio of the transmitted flux to the incident one can be written as:

$$T(E) = \left| \frac{A_{i+1} k_{i+1}}{A_i k_i} \right|^2$$

(8)

where 0 and $N$ are indexes corresponding to the in-coming and the out-going electron waves respectively. The amplitudes $A_i$ and $A_0$ are related through:

$$\begin{bmatrix}A_N \\ B_N \end{bmatrix} = \prod_{i=0 \ldots N-1} M_i \begin{bmatrix}A_0 \\ B_0 \end{bmatrix}.$$ 

(9)

Thus, the tunneling current density can be determined by [30]:

$$J(V_{bias}) = \frac{e m_k g T}{2\pi^2 h^2} \int_0^{+\infty} T(E) \ln \left(\frac{1 + \exp (E_F - E)/k_B T}{1 + \exp (E_F - E - e V_{bias})/k_B T}\right) dE$$

(10)

where $V_{bias}$ is the linear applied voltage across the active region, and the transmission coefficient $T(E)$ is calculated for the specific value of $V_{bias}$.

3. Results and discussion

To investigate this electron transport model, we have considered the polarization effect on the n-type InGaN/AlGaN RTDs. The parameters used in our calculations of the electron transport through AlGaN/InGaN/AlGaN/InGaN/AlGaN/AlGaN RTD are taken from Ref. [31,32] and summarized in Table 1. The donor concentration in the n-type Al$_{0.15}$Ga$_{0.85}$N is taken equal to $3 \times 10^{18}$ cm$^{-3}$. The energy band diagram of the device under an external applied voltage $V_{bias}$ as well as the charge carrier transfer mechanisms included in the transport model are schematically shown in Fig. 2. The elastic tunneling (mechanism (1)) occurring when an electron energy level coincides with the energy levels in the In$_{0.15}$Ga$_{0.85}$N central quantum well is supposed to be a general carrier transfer process. The second mechanism of tunneling (mechanism (2)) in Fig. 2 corresponds to the electron tunneling from the localized states in In$_{0.5}$Ga$_{0.5}$N regions through the Al$_x$Ga$_{1-x}$N/In$_{0.15}$Ga$_{0.85}$N/Al$_x$Ga$_{1-x}$N stack. In fact, the pre-confinement regions In$_{0.15}$Ga$_{0.85}$N before and after the Al$_x$Ga$_{1-x}$N stack accumulate electrons which fill the localized states having energy near the bottom of the In$_{0.15}$Ga$_{0.85}$N well. Moreover, we note that the barrier height is a key parameter for thermally activated emission. In fact a reduction of the height of the barrier offers the possibility of efficient thermally activated emission over the barrier depending on temperature, doping and interface quality (mechanism (3)).

In the first step, to assess the transport of current in this modeled RTD, we have calculated the electron transmission coefficient $T$ as a function of the energy without polarization. Results of calculations in the InGaN/AlGaN RTD structure with 3.5 nm Al$_x$Ga$_{1-x}$N barrier thick ($0.3 < x < 0.5$) are illustrated in Fig. 3 and show two peaks in the transmission probability curve. As known, the transmission peaks
Table 1
Parameters of n-type InGaN/AlGaN RTD structures.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conduction band energy of Al(<em>{0.15})Ga(</em>{0.85})N barrier</td>
<td>0.1–2.8 eV</td>
</tr>
<tr>
<td>Conduction band energy at In(<em>{0.1})Ga(</em>{0.9})/Al(<em>{0.15})Ga(</em>{0.85})N injecting contact</td>
<td>0.305 eV</td>
</tr>
<tr>
<td>Effective mass, m(^*) (Al(<em>{0.15})Ga(</em>{0.85})N)</td>
<td>0.133 m(_0)</td>
</tr>
<tr>
<td>Effective mass, m(^*) (Al(<em>{0.15})Ga(</em>{0.85})N)</td>
<td>0.143 m(_0)</td>
</tr>
<tr>
<td>Effective mass, m(^*) (Al(<em>{0.15})Ga(</em>{0.85})N)</td>
<td>0.150 m(_0)</td>
</tr>
<tr>
<td>Effective mass, m(^*) (Al(<em>{0.15})Ga(</em>{0.85})N)</td>
<td>0.159 m(_0)</td>
</tr>
<tr>
<td>Thickness of In(<em>{0.1})Ga(</em>{0.9})N pre-confinement region, d(_1)</td>
<td>10 nm</td>
</tr>
<tr>
<td>Thickness of potential Al(<em>{0.3})Ga(</em>{0.7})N barrier, d(_2)</td>
<td>3.5 nm</td>
</tr>
<tr>
<td>Thickness of In(<em>{0.1})Ga(</em>{0.9})N middle quantum well, d(_3)</td>
<td>5 nm</td>
</tr>
<tr>
<td>Temperature T</td>
<td>300 K</td>
</tr>
</tbody>
</table>

Fig. 2. The n-type InGaN/AlGaN RTD energy band diagram under an external bias and carrier behavior: (1) is the tunneling transfer from extended states, (2) is the tunneling transfer from the localized states in the pre-confinement region, and (3) is the thermally activated carrier transport.

Fig. 3. The transmission coefficient versus electron energy, at 300 K, for 5 nm width In\(_{0.1}\)Ga\(_{0.9}\)N middle quantum well with different Al compositions in the barriers.

correspond to resonances with the eigenenergies of the wells. The transmission coefficient decreases when the Al content increases and shifts to higher energies. In fact, the decrease of transmission probability at resonance is due to an enlargement of the region depleted and an increase of the barrier heights. For a symmetric double barrier the transmission coefficient is equal to unity at resonance. However an asymmetric double barrier the transmission at resonance is less than unity, probably due to the piezoelectric effect in cubic III-nitride compounds that modify the potentials profile and being equal to \( T = T_{low}/T_{high} \) where \( T_{low} \) and \( T_{high} \) are the smaller and the larger transmission coefficients of the two barrier respectively [33].

Next, we have calculated the current density. Fig. 4 illustrates the voltage–current density characteristics for different Al concentrations and shows a current density decreases when the Al content increases. We note that not only barrier potentials increase with the rate of Al, but also the band profile is shifted to high energies. This behavior can be explained by the fact that, when the quasi-Fermi level of the emitter is slightly above the well resonant condition, only a very small part of electrons overcomes the double barrier. The current valley is reduced which increases the peak-to-valley ratios. Therefore, we can deduce that more the confinement increases, the peak-to-valley ratios increase. This results in a shift of the peak current to smaller voltages with a corresponding increase of the peak current density. However, the significant dispersion of the resonant level with the lowering of the potential barrier height leads to a broadening of the
Table 2

<table>
<thead>
<tr>
<th>x</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J_{\text{max}}/J_{\text{min}})</td>
<td>1.99</td>
<td>2.22</td>
<td>2.45</td>
</tr>
</tbody>
</table>

Fig. 4. Current density as a function of the applied bias, at room temperature, for the n-Al\(_0.15\)Ga\(_{0.85}\)N/\(\text{InGa}\)\(_{0.1}\)Ga\(_{0.9}\)N middle quantum well (5 nm) with different Al composition \(x\) in the barriers.

Fig. 5. The thermally activated current density as a function of the potential barrier height \(\Delta E_c\) for n-type InGaN/AlGaN RTDs at \(T = 300\) K with different values of conduction band energy at In\(_{0.1}\)Ga\(_{0.9}\)N/Al\(_{1-x}\)Ga\(_x\)N/In\(_{0.1}\)Ga\(_{0.9}\)N/Al\(_{1-x}\)Ga\(_x\)N/In\(_{0.1}\)Ga\(_{0.9}\)N/n-Al\(_{0.15}\)Ga\(_{0.85}\)N RTD structures (0.3 \(\leq x \leq 0.5\)).

resonant peaks and a decrease of the \(J_{\text{max}}/J_{\text{min}}\). Further, the values of the \(J_{\text{max}}/J_{\text{min}}\) peak-to-valley ratios for the 5 nm thick QW\(_2\) for the RTD structure with different Al compositions in the barriers are listed in Table 2.

Afterward, we have estimated the thermally active current in this RTD at room temperature. To regulate the thermally activated current in this structure, we have considered the appropriate relation between the overall potential barrier height and the conduction band offset at the relaxed type injecting contact. The results of our simulations of the thermally active current are plotted versus electron energy in Fig. 5.

This component of current undergoes an exponential drop when the potential barrier height increases as given by Eq. (5). But, for a fixed value of the injector and collector composition, increasing the band offset of the barrier between injecting contact and pre-confinement InGaN regions leads to a slightly increase in the thermally activated current.

Therefore, we can conclude that the transport of current in the InGaN/AlGaN RTD structure is optimal for 30% of Al composition in the barriers. For this reason, we have deduced the electron transport in a 2D–2D resonant tunneling diode of the designed n-type InGaN/AlGaN RTD with 3.5 nm Al\(_{0.3}\)Ga\(_{0.7}\)N barriers thick at room temperature. Fig. 6 illustrates the simulation of the RTD’s conduction band edges at room temperature when no electric field is applied. In the energy-band diagram, we plot the subband energies with their envelope wave functions and the Fermi level. It can be seen that the QW\(_1\), as well as the QW\(_2\), contains four confined levels. One can note that among these levels only two lie below the Fermi level, resulting in the formation of a two-dimensional electron gas in these channels. However, the central well (QW\(_2\)) presents a two confined levels one of which is under the Fermi level at zero bias.
Fig. 6. The conduction band profile, Fermi levels, and electron subbands with relative wave functions for In$_{0.1}$Ga$_{0.9}$N middle quantum well (5 nm) and Al$_{0.3}$Ga$_{0.7}$N barriers.

Fig. 7. (a) Room temperature evolution of Fermi level position and fundamental energy levels in the quantum wells ($e_{11}$, $e_{12}$, $e_{13}$) as a function of an applied bias voltage. (b) Band-gap diagram, subband energies with their wave functions, calculated for applied bias voltage $V_{\text{bias}} = 0.6$ V.

To analyze this resonant tunneling process, we have investigated the influence of an applied electric field on the energy levels, subband occupancies, and the electronic charge transfer. In Fig. 7(a), we report the evolution of the energy levels as well as the Fermi level as a function of an applied bias voltage. It is seen that the fundamental electron subband energies and the Fermi level in the three QWs shift positively. This shift in energy of subbands in QW$_2$ and in QW$_3$ is larger than that in the QW$_1$. At $V_{\text{bias}} = 0.6$ V the Fermi level and the subband energy $e_{13}$ in QW$_3$ are crossing. Furthermore, we have plotted the band diagram, the subband energies with their wave functions, under applied bias voltage $V_{\text{bias}} = 0.6$ V in Fig. 7(b).
In order to illustrate the space charge rearrangement, we have calculated the local electron density $n(z)$ in the RTD structure at room temperature. The results are plotted versus the bias voltage in Fig. 8. This bias voltage is varying from 0 to 1 V by steps of 0.2 V. At zero bias, we can see that the local electron density presents the same values in QW$_3$ and in QW$_1$; however, it appears a little less in QW$_2$. Under applied bias voltage, the QW$_3$ electron sheet density decreases on the right-hand side to be finally transferred to the left-hand side quantum well one QW$_1$, whereas QW$_2$ remains with constant population. This charge transfer is established in the opposite direction to bias voltage and is attributed to the resonant tunneling process through the two barriers. In fact, when increasing the bias voltage, an energy level in QW3 shifts progressively. As a result, resonant tunneling can be revealed leading to a 2D–2D electron transfer. From the results presented above (Fig. 7), it is clear that we expect to observe resonant tunneling through the quantized subbands in QW3 for bias voltage values close to 0.6 V. Moreover, we note that the fundamental energy level in the emitter (QW$_3$), $e_{13}$ crossed with the Fermi level in the emitter at bias voltage approximately equal to 0.6 V, and above this value become practically unpopulated. On the contrary, it is seen that under an applied bias voltage greater to 0.6 V, the fundamental energy level $e_{11}$ in the collector (QW$_1$) is under the Fermi level. As a result, the transfer in the considered RTD structure entails the filling of the accumulation layer close to the emitter contact and the resonance between the quantized subbands in the active zone.

We have also investigated the influence of the applied bias voltage on the subband occupancies. For this, we have calculated the total electron density $n_s$ in 300 K as a function of the applied voltage varying from 0 to 1 V, as displayed in Fig. 9. The total electron densities of QW$_1$ and QW$_3$ are equal and its value is $(7.5 \times 10^{12} \text{ cm}^{-2})$ without an applied bias voltage, while in QW$_2$ the total electron density is $(3 \times 10^{12} \text{ cm}^{-2})$ and it decreases slightly when the bias voltage increases. As the bias voltage increases, the total electron density of QW$_3$ decreases rapidly. Thus, it is important to note that the tunneling-induced charge transfer between QW$_3$ and QW$_1$ is produced under low bias voltage through the central well (QW$_2$) due to resonance tunneling under low bias voltage at room temperature.

4. Conclusion

In conclusion, we have theoretically studied the electronic transport in cubic InGaN/AlGaN RTDs. This electronic RTD consists of a three In$_{0.1}$Ga$_{0.9}$N quantum wells (QWs) separated by two Al$_x$Ga$_{1-x}$N barriers, $0.3 \leq x \leq 0.5$ for the strained part of the structure; the whole is embedded between n-type relaxed Al$_{0.15}$Ga$_{0.85}$N. Our calculations were performed on the basis of a self-consistent solver of the Schrödinger, Poisson and kinetics equations. The current resonance dependency on the applied voltage as well as the double barrier

\[ \text{Fig. 8. Bias voltage dependence of the local density } n(z) \text{ of confined electrons in the RTD structure calculated at 300 K. The bias voltage is varying from 0 to 1 V by steps of 0.2 V.} \]

\[ \text{Fig. 9. Total electron density } n_s \text{ in each quantum wells calculated versus the bias voltage at room temperature.} \]
height has been instigated. The simulation has shown an insignificant contribution of the electron transfer from states localized in the InGaN well due to the high potential barrier at $\text{In}_{0.1}\text{Ga}_{0.9}\text{N}/\text{Al}_{x}\text{Ga}_{1-x}\text{N}$ interface. We have also shown that a high Al composition in the double barrier improves the peak-to-valley ratio due to the large reduction in the valley current. Our results demonstrate the possibility for a realistic tuning of the thermally activated transfer in this RTD device. Next, we have proved that the structure composed of three $\text{In}_{0.1}\text{Ga}_{0.9}\text{N}$ quantum wells separated by two barriers $\text{Al}_{0.3}\text{Ga}_{0.7}\text{N}$ and embedded between $n$-type $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ injector and collector layers is a potential candidate for achieving a resonant tunneling diode. However, it is appropriate that the studies take into account both contributions of 3D extended states in the emitter region and the 2D quantum-confined states to the tunneling mechanism.

References