Vertical transport in GaAs/Ga$_{1-y}$Al$_y$As barrier structures containing quantum wells: Current–temperature characteristics

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**Abstract**

Vertical transport in GaAs/Ga$_{1-y}$Al$_y$As barrier structures was investigated using current–temperature ($I$–$T$) measurements in the dark. The samples studied had 500 Å thick Ga$_{1-y}$Al$_y$As ($0 \leq y \leq 0.26$) linearly graded barriers between the n$^+$-GaAs contacts and the Ga$_{0.74}$Al$_{0.26}$As central barrier containing $N_w$ ($=0, 4, 7$ and $10$) n-doped GaAs quantum wells of width 35 Å. The thickness of Ga$_{0.74}$Al$_{0.26}$As barrier between the wells was 310, 135 and 77 Å for the samples with $N_w =$ 4, 7 and 10, respectively. The vertical current was measured as a function of temperature (3.5–295 K) at applied voltages in the range 0.01–0.7 V. The total barrier height ($\Delta U_{m}$) and the space charge density in the sample with $N_w =$ 0, and the effective barrier height ($\Delta E$) for the samples with $N_w =$ 4, 7 and 10 were determined by analysing the experimental $I$–$T$ characteristics using drift–diffusion theory for thermal current. The variation of $\Delta U_{m}$ and $\Delta E$ with applied voltage was discussed in connection with various dark current mechanisms in barrier structures, including thermionic emission, Fowler–Nordheim tunnelling and sequential resonant tunnelling.

**1. Introduction**

Investigation of vertical transport in barrier structures containing quantum wells is of great importance in understanding the physical properties of various advanced electronic devices such as...
quantum well infrared photodetectors (QWIPs), heterostructure bipolar transistors, semiconductor lasers, and hot electron transistors (for review see [1,2]). For instance, the dark current is an important parameter for the performance of QWIPs, because the dark current determines the signal-to-noise ratio of the device. Therefore, it is important to understand the role played by thermionic emission and tunnelling contributions to the dark current in order to optimise the structure.

Barrier structures with abrupt, rectangular potential barrier have been studied extensively [3–9]. A few studies have been devoted to symmetrical triangular barriers and asymmetrical sawtooth-shaped barrier structures [10,11]. Recently, Ridley and coworkers [12–16] investigated the vertical transport in GaAs/Ga$_{1−y}$Al$_y$As symmetrical barrier structures with linearly-graded barriers grown between the n$^+$-GaAs contacts and the central barrier containing up to 10 quantum wells. Bishop et al. [14] measured the dark current as a function of temperature (I–T characteristics) in the range 77–300 K at low applied voltage (0.01–0.4 V). The present study is largely motivated by the need for accurate measurements of the dark current in these barrier structures at low temperature and high voltage.

This paper presents the results of systematic I–T measurements in the dark in the temperature range from 3.5 to 295 K, at selected applied voltages from 0.01 to 0.7 V, for barrier structure samples prepared from the same wafers as those used in [14]. One aim was to investigate the effects of varying the number of quantum wells in the central barrier on the I–T characteristics of the samples having the same well width. The barrier height was determined as a function of the applied voltage by analysing the experimental I–T data within the framework of drift–diffusion theory for thermionic emission. We also attempted to determine the temperature and voltage ranges in which various vertical transport mechanisms are in effect. The results shed further light on the understanding of the relative importance of dark current mechanisms in these barrier structures, including thermionic emission, ground state sequential resonant tunnelling and Fowler–Nordheim tunnelling.

### 2. Experimental procedure

The barrier structures investigated in the present study were grown by the MOVPE technique. For further details of sample preparation refer to Bishop et al. [14]. The layer structure of the samples is shown in [Fig. 1. A 1 µm thick heavily doped n$^+$-GaAs contact layer was deposited on n$^+$-GaAs substrate. The barrier structure was then grown on this layer in three stages: (i) a 500 Å thick Ga$_{1−y}$Al$_y$As graded barrier in which the Al concentration (y) increased linearly from 0 to 0.26, (ii) Ga$_{0.74}$Al$_{0.26}$As central barrier containing $N_w$ (=0, 4, 7 and 10) n-doped GaAs quantum wells, and (iii) a 500 Å thick Ga$_{1−y}$Al$_y$As graded barrier in which y decreased linearly from 0.26 to 0. Finally, a 1 µm thick heavily doped n$^+$-GaAs contact was deposited on the graded barrier. The samples were fabricated in the circular mesa geometry. Structural properties of the samples are given in Table 1.

All barrier layers were nominally undoped. The doping density in the n$^+$-GaAs contacts was of the order of 1 × 10$^{24}$ m$^{-3}$ (Table 1). To prevent the formation of space charge in the central barrier, the quantum wells in the samples with $N_w$ = 4, 7 and 10 were n-type doped to a level of 5 × 10$^{23}$ m$^{-3}$ [14,15]. All barrier structures containing quantum wells were designed to have only one energy-subband in the wells. Assuming that 60% of the bandgap difference is associated with the conduction band [17], when $y = 0.26$, the conduction bandgap discontinuity is $ΔE_c = 220$ meV. Calculations using the Kronig–Penney model [18] yielded the ground subband energy $E_1$ and its width $ΔE_1$.

### Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of quantum wells $N_w$</th>
<th>Thickness of the barrier between the wells $L_b$ (Å)</th>
<th>Quantum well width $L_W$ (Å)</th>
<th>Total thickness of barrier layers $L$ (Å)</th>
<th>Doping density in contact layers ($10^{23}$ m$^{-3}$)</th>
<th>Ground subband energy $E_1$ (meV)</th>
<th>Width of the ground subband $ΔE_1$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QT680A</td>
<td>0</td>
<td>–</td>
<td>–</td>
<td>2084</td>
<td>8</td>
<td>–</td>
<td>–</td>
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<tr>
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<td>4</td>
<td>310</td>
<td>35</td>
<td>2070</td>
<td>9</td>
<td>102.3</td>
<td>&lt;0.05</td>
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<tr>
<td>QT680C</td>
<td>7</td>
<td>135</td>
<td>35</td>
<td>2055</td>
<td>7</td>
<td>105.3</td>
<td>0.2</td>
</tr>
<tr>
<td>QT680B</td>
<td>10</td>
<td>77</td>
<td>35</td>
<td>2043</td>
<td>8</td>
<td>103.5</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Fig. 1. The layer structure of the samples used in the study. The thickness of the central barrier \((L_C)\) is 1084, 1070, 1055 and 1043 Å for the samples with \(N_w = 0, 4, 7\) and 10, respectively. (Table 1). The width of the ground subband for the samples with \(N_w = 4, 7\) and 10 is much smaller than the collision broadening \((\hbar/\tau \approx 15\ \text{meV})\) determined from vertical mobility measurements [19]. This implies that the electronic states are essentially localised in the ground subband [20,21]. Therefore, miniband conduction is not expected in these samples.

The current–temperature \((I–T)\) measurements were carried out in the dark in the range 3.5–295 K at selected applied voltages from 0.01 to 0.7 V. All measurements were performed in a closed-cycle refrigeration system (HS-4 Heliplex, APD Cryogenics) using a source/measure unit (Keithley 236).

3. Theoretical background

Thermionic emission and tunnelling are the two main dark current mechanisms in GaAs/\(Ga_{1-y}Al_y\)As barrier structures (see [1]). The former becomes dominant at high temperature and low voltage, while the latter becomes dominant at low temperature and high voltage. Most previous studies used the standard thermionic emission theory [22] to analyse the \(I–T\) characteristics measured in various barrier structures [3,4,7,9,11,17]. However, for thick barriers, in which the electron mean free path is much smaller than the barrier thickness, collisions in the barrier are expected to dominate the vertical transport. In this case, the drift–diffusion theory is more appropriate to evaluate the thermally activated current [12,14]. In the following, the approximate analytical expressions that we used to analyse the \(I–T\) characteristics measured for the barrier structures investigated in this study are briefly outlined for the sake of convenience.

When there are unintentionally doped acceptors in the barrier layer, the electrons coming from the \(n^+\)-GaAs contact via diffusion can be trapped by the acceptors and hence create a negative space charge in the barrier. The effect of negative space charge is to increase the barrier height for thermionic
emission over the barrier [4,12,14,17,23]. There is also a small contribution from the dipole field, which forms at the interface between the contact and the barrier [4,12,14]. However, the barrier height enhancement due to the dipole field is very small when compared to that of the space charge contribution [12,14]. By assuming that the space charge is uniformly distributed throughout the central barrier and absent elsewhere in the structure, Daniels et al. [12] calculated the thermally activated current on the basis of drift–diffusion theory. They derived the following expression for the thermal current in plain barrier structure which does not contain quantum wells ($N_w = 0$):

$$\ln\left(\frac{J}{T^{1/2}}\right) = -\frac{n_0}{2^{3/2}N_{c0}} - \frac{1}{k_B T} \left(\Delta U_m - \frac{eV_S}{2}\right) + \ln B$$

(1)

with

$$N_{c0} = \left(\frac{m^* k_B T}{2\pi \hbar^2}\right)^{3/2}.$$  

(2)

Here $J$ is the current density, $T$ is the absolute temperature, $n_0$ and $N_{c0}$ are the doping density and effective density of states in the $n^+$-GaAs contacts, respectively, $k_B$ is the Boltzmann constant, $\Delta U_m$ is the total barrier height, $e$ is the magnitude of the electron charge, $V_S$ is the applied voltage, and $m^*$ is the electron effective mass in the contacts. The $\Delta U_m$ is the sum of the conduction bandgap discontinuity and the additional barrier height enhancements due to the negative space charge and dipole field, and is defined with respect to the conduction band-edge of the $n^+$-GaAs contact. The quantity $B$ in Eq. (1) is proportional to the product $n_0 \mu N_S^{1/2}$, where $\mu$ is the electron mobility in vertical transport and $N_S$ is the space charge density. Hence, the term $\ln B$ is only weakly temperature dependent through the mobility. A plot of the left-hand side of Eq. (1) against reciprocal temperature will give a straight line from whose slope the total barrier height $\Delta U_m$ can be deduced. Having determined $\Delta U_m$, the space charge density can be obtained from [12]

$$N_S = \frac{2\varepsilon_S \varepsilon_0 (\Delta U_m - \Delta E_c)}{e^2 (X_2^2 - X_1^2)}.$$  

(3)

where $\varepsilon_S$ is the static dielectric constant of $\text{Ga}_x\text{Al}_{1-x}\text{As}$, $\varepsilon_0$ is the permittivity of vacuum, $X_1$ is the thickness of the graded barrier and $X_2$ is the distance from the centre of the central barrier to the $n^+$-GaAs contact (see Fig. 1).

As in the case of the plain barrier structures, the thermally activated current in the barrier structures containing quantum wells can be described by the drift–diffusion theory. Bishop et al. [14,16] divided the barrier structures into the three regions (see Fig. 1), which behave like three resistances connected in series, and calculated the thermal current in each region using the drift–diffusion theory, by assuming that no space charge is formed in the barriers. When a voltage $V_S$ is applied to the sample, under the assumption that there is no voltage drop across the $n^+$-GaAs contacts, the overall voltage across the barrier layers is $V_S = V_1 + V_2 + V_3$. Here $V_1$, $V_2$ and $V_3$ are the voltages dropped across region I (first graded barrier), region II (central barrier containing quantum wells) and region III (second graded barrier), respectively. The voltage distribution across the barrier structure is dependent upon the relative importance of thermal and tunnelling contributions to the vertical current. Bishop et al. [14] showed that, at high temperature and low voltage, when thermionic emission dominates over the whole structure, most of the applied voltage is dropped across region II, that is $V_2 \gg (V_1 + V_3)$. This suggests that the vertical current is essentially determined by the resistance of region II. Therefore, the effective barrier height $\Delta E = \Delta E_c - E_F$ of the samples containing 4, 7 and 10 quantum wells can be determined by comparing the experimental $I–T$ characteristics with the following expression derived for the thermal current in the central region [14,16]

$$I = e\mu n_0 A \frac{V_{2p}}{L_W + L_B} \exp\left(-\frac{\Delta E_c - E_F}{k_B T}\right).$$  

(4)

Here $A$ is the area of the mesa contact, $V_{2p}$ is the voltage drop across one period ($L_W + L_B$) of the multiple quantum wells (MQWs) in region II, and $E_F$ is the Fermi energy of the $n^+$-GaAs contact. When no space
charge is formed in the barrier, the effective barrier height is defined with respect to the Fermi level of the contact.

At low temperature and high voltage, the vertical transport in plain barrier structures occurs via tunnelling, which takes the form of the Fowler–Nordheim (F–N) emission under high enough electric field [24, 25]. The F–N tunnelling current density in a rectangular barrier can be represented by

\[
J = \frac{e^3 F^2}{16\pi^2 h (\Delta E_c - E_F)} \exp\left[ -\frac{4 (2m^*_b)^{1/2}}{3\hbar F} (\Delta E_c - E_F)^{3/2} \right],
\]

where \( F \) is the applied electric field and \( m^*_b \) is the electron effective mass in the barrier. Eq. (5) also applies to the barrier structures containing quantum wells, if \( E_F \) is replaced by the ground subband energy \( (E_1) \) of the wells [7, 9, 16]. The F–N tunnelling current is temperature independent. If the thickness of the barrier layer between the adjacent quantum wells is small enough, the sequential resonant tunnelling (SRT) [5, 6, 8, 16] also contributes to the vertical transport in barrier structures containing MQWs. The vertical current due to SRT is also insensitive to temperature. The contribution of SRT to the dark current can be effectively reduced by increasing the thickness of the barrier between the wells in the MQWs [26–28].

4. Results and discussion

Examples for the current–temperature (\( I–T \)) characteristics of the barrier structure samples determined at selected applied voltages are presented in Fig. 2. As the figure demonstrates, at the

![Fig. 2. Current–temperature (\( I–T \)) characteristics measured at selected applied voltages (\( V_S \)) for the barrier structure samples containing (a) \( N_w = 0 \), (b) 4, (c) 7 and (d) 10 quantum wells in the central barrier. The vertical arrow marks the temperature below which the vertical current is essentially constant or varies slowly with temperature.](image)
Determination of the total barrier height ($\Delta U_m$) of the sample with $N_w = 0$ from the $I$–$T$ characteristics measured at $V_S = 0.01$ V and 0.2 V. The straight line is the best fit of Eq. (1) to the experimental data.

The $I$–$T$ characteristics measured at $V_S \geq 0.3$ V and 0.7 V for the samples with $N_w = 0$ and 4, respectively, show a tendency to saturate at temperatures below about 30 K (Fig. 2(a) and (b)). This finding suggests that, at low temperature and high voltage, the temperature dependence of the dark current is reduced due to the onset of tunnelling. The vertical current measured at high voltage (>0.3 V) for the samples with $N_w = 7$ and 10 is insensitive to temperature below about 80 K (Fig. 2(c) and (d)). Because thermally activated current is negligible at low temperatures, the constant dark current can be attributed to the ground state SRT, which is temperature independent [1,5,6].

By using the experimental data for the electron mobility in vertical transport [19], we estimated that the electron mean free path is much smaller than the thickness of the central barrier of all the samples used in the present study. Thus, we used Eqs. (1) and (4) to analyze the $I$–$T$ characteristics measured at low voltage and high temperature, where the thermally activated current is the major component. Optical–phonon assisted tunnelling [1,6] was neglected in the data analysis. This is because, the optical–phonon assisted tunnelling mechanism predicts a value for the vertical mobility at room temperature [21,29], which is about two orders of magnitude smaller than the mobility measured for our samples [19]. The contribution of optical phonon-assisted tunneling to vertical current is expected to be negligibly small [1,6] when compared to that of thermionic emission.

4.1. Total barrier height and space charge density in the plain barrier structure ($N_w = 0$)

Geometric magnetoresistance measurements [19] showed that the space charge effect is important in the determination of the mobility of electrons in the plain barrier structure sample ($N_w = 0$). Therefore, Eq. (1) was used to analyse the experimental $I$–$T$ characteristics of this sample. To this aim, the experimental $I$–$T$ data (Fig. 2(a)) were converted to current density–temperature (J–T) data, and $[\ln(J/T^{1/2}) - n_0/2^{3/2}N_c0]$ was plotted versus $1/T$ (Fig. 3). Eq. (1) was fitted to the experimental data using the least-squares method by taking $\Delta U_m$ as an adjustable parameter. Then the total barrier height $\Delta U_m$ was determined from the slope of the best-fit straight line. The experimental $I$–$T$ curve measured at 0.01 V yielded the value of 240 meV for $\Delta U_m$, which is substantially larger than the conduction bandgap discontinuity ($\Delta E_c = 220$ meV). The difference between $\Delta U_m$ and $\Delta E_c$...
The variation of the total barrier height ($\Delta U_m$) with applied voltage for the sample with $N_w = 0$. The full curve is the parabola that best fits to the experimental data points. The space charge density $N_S = 4.4 \times 10^{21} \text{ m}^{-3}$ was determined by using the value found for $\Delta U_m$ in Eq. (3). The values obtained in the present study for $\Delta U_m$ and $N_S$ from I–T measurements at 0.01 V are comparable to those reported \[14\] for a similar sample.

Following the same procedure, the total barrier height $\Delta U_m$ for the sample with $N_w = 0$ was determined as a function of the applied voltage (Fig. 4). The value of $\Delta U_m$ remains approximately constant below about 0.07 V, and decreases rapidly when the applied voltage is increased. Although the $I$–$T$ curve obtained at 0.4 V demonstrates that there still exists a potential barrier for thermionic emission (see Fig. 2(a)), it was not possible to deduce a value for $\Delta U_m$. Bishop et al. \[14\] noted that the total barrier height of their sample with $N_w = 0$ decreased with applied voltage, and the potential barrier was effectively removed at 0.5 V. However, they did not provide experimental data to support this conclusion.

When a voltage is applied to the sample with $N_w = 0$, the voltage drop initially occurs across the graded barrier, reducing the slope of its conduction band-edge (and hence the barrier height), and allowing increased thermionic emission over the barrier [11,30]. Increasing the applied voltage will further flatten the graded barrier and increase the thermionic current. Therefore, the plain barrier structure having graded barriers between the contacts and the central barrier differs substantially from the one with an abrupt interface in that the barrier height of the former can be lowered or raised by application of a voltage across the structure. Whereas, the height of an abrupt potential barrier decreases only slightly with applied voltage \[3,17,23\], because the applied voltage produces no voltage drop across the vanishingly small distance of the abrupt interface [11,14]. Therefore, it can be concluded that the exponential dependence of the vertical current on temperature seen at applied voltages in the range 0.1–0.3 V (Fig. 2(a)) is of the form expected for thermionic emission over a voltage-controlled barrier.

The tunnelling probability through a rectangular barrier is an exponentially decaying function of the barrier thickness and the barrier height (see for example \[20,25\]). Since the central barrier of the sample with $N_w = 0$ is very thick (1084 Å), the transmission coefficient of this barrier is practically zero. Nevertheless, at low temperature, when the applied voltage is increased above 0.3 V, the tunnelling (through the tip of the triangular potential barrier) can contribute to the vertical transport. Therefore, the very high vertical current, which increases rather slowly with temperature (see Fig. 2(a), the portion below 30 K of the $I$–$T$ curves measured at 0.3 and 0.4 V) can be ascribed to tunnelling.

The dark current in various GaAs/Ga$_{1-y}$Al$_y$As plain barrier structures with rectangular potential barrier has been investigated in several studies \[4,23,31–33\]. For samples with a 134 Å thick barrier, Hase et al. \[23\] observed temperature-independent current in the range 70–150 K, and attributed it to tunnelling. However, in the same study, constant current was not observed in another sample.
in which the barrier thickness was 300 Å. Feng et al. [32] reported that samples with 200 Å thick barrier exhibited a constant current below 100 K, and ascribed it to tunnel emission operative at high voltage. However, they stressed that the F–N tunnelling formula applied approximately only below 40 K. Chaabane et al. [31] argued that, for samples with 200 Å thick barrier, the F–N tunnelling regime should apply typically below 80 K. Temperature-independent dark current was not reported for samples with thick (>200 Å) barrier [4,31,33]. Because the central barrier of the sample with \( N_w = 0 \) investigated in the present study is very thick, temperature-independent current was observed only below 20 K.

4.2. Effective barrier height of the barrier structure samples containing quantum wells

To determine the effective barrier height (\( \Delta E \)) of the barrier structure samples containing \( N_w = 4, 7 \) and 10 quantum wells in the central region, Eq. (4) was fitted to the experimental \( \ln(I) \) versus \( 1/T \) plot by taking \( \Delta E \) as an adjustable parameter (Figs. 5–7). The effective barrier height was determined from the slope of the straight line that best fits the experimental data. The \( I–T \) characteristics measured at low applied voltage (0.01–0.2 V) fit well to Eq. (4), indicating that thermionic emission is the major vertical transport mechanism.
Fig. 7. Determination of the effective barrier height ($\Delta E$) for the sample with $N_w = 10$ from the $I$–$T$ characteristics measured at (a) $V_S = 0.01$ V and (b) $V_S = 0.4$ V. The symbols denote the experimental data and the straight line is the best fit of Eq. (4) to experimental data.

Fig. 8. The variation of the effective barrier height ($\Delta E$) with applied voltage for the samples containing $N_w = 4$, 7 and 10 quantum wells. The symbols represent the experimental data and the full curves through the experimental data points are intended to be a guide to the eye.

The experimental ln($I$) versus $1/T$ plots for the samples with $N_w = 4$, 7 and 10 deviate from the expected linear behaviour (Eq. (4)) at temperatures higher than that marked by arrow A in Figs. 5–7. The origin of this discrepancy could be the decrease of electron mobility with increasing the temperature above about 220 K [19]. At high voltage, a deviation of the experimental data from Eq. (4) was observed at temperatures lower than that marked by arrow B in Figs. 5(b), 6(b), and 7(b). This deviation is consistent with tunnelling, which unlike thermionic emission has no temperature dependence.

Analysis of the experimental $I$–$T$ data using Eq. (4) allowed the determination of the effective barrier height $\Delta E$ up to 0.4 V for the samples with $N_w = 7$ and 10, and up to 0.7 V for the sample with $N_w = 4$ (Fig. 8). The $\Delta E$ values determined at 0.01 V for the samples with $N_w = 4$, 7 and 10, which are in good agreement with those reported in [14] for similar samples, are consistent with the expected barrier height $\Delta E_c - E_F \approx 170$ meV. This experimental finding also implies that four quantum wells are enough to eliminate the formation of negative space charge in the central barrier [14]. The effective barrier height determined for the samples with $N_w = 7$ and 10 initially decreases with increasing voltage and tends to level off at about 130 meV in the range $V_S \geq 0.2$ V (Fig. 8). The latter value of $\Delta E$ is only 11% higher than $\Delta E_c - E_F \approx 117$ meV. On the other hand, as the voltage applied to the sample with $N_w = 4$ was increased from 0.01 to 0.7 V the effective barrier height decreased from 150 meV down to 72 meV with a progressively decreasing slope (Fig. 8).
4.3. Discussion of the vertical current mechanisms as functions of temperature and applied voltage

The experimental data and interpretations presented above suggest that understanding of the variation of the effective barrier height with applied voltage is important in acquiring information on vertical transport mechanisms which are in effect in the samples with \( N_w = 4, 7 \) and 10. When the voltage \( (V_S) \) applied to the samples with \( N_w = 7 \) and 10 is low enough, the Fermi level of the n+–GaAs contact (cathode) is located below the ground subband \( E_1 \) in the quantum wells: \( E_F < E_1 \). Under this condition the possibility of electron tunnelling through the graded barrier (region I) is very low; therefore, if the temperature is high enough, the vertical current is generated solely by thermionic emission. As a consequence, the effective barrier height \( \Delta E \) becomes comparable to \( \Delta E_s - E_F \). As the applied voltage is increased, the slope of the conduction band-edge of the graded barrier decreases and hence the Fermi level \( E_F \) rises towards \( E_1 \). Therefore, the initial decrease of \( \Delta E \) can be ascribed to the voltage drop across the graded barrier. Eventually, at a certain value of \( V_s \) the Fermi level matches the ground subband of the quantum wells: \( E_F \cong E_1 \), hence, the effective barrier height becomes equal to \( \Delta E_s - E_1 \). Once the condition \( E_F \cong E_1 \) is accomplished, the electrons in the contact (i) tunnel through the graded barrier and transfer to the ground subband of the first quantum well, (ii) tunnel through MQWs (region II) by ground state SRT and (iii) reach the anode by F–N tunnelling through the graded barrier (region III). When the applied voltage is increased further, the slope of the conduction band-edge of the graded barrier (region I) does not decrease any more. As a consequence of this, the effective barrier height becomes practically independent of applied voltage. Accordingly, the constant vertical current measured at \( V_S \geq 0.3 \) V in the temperature range from 3.5 to about 80 K (Fig. 2(c) and (d)) can be ascribed to F–N tunnelling through the graded barriers and to ground state SRT through MQWs. Previously, the temperature–independent dark current observed at temperatures below 100 K in GaAs/Ga\(_{1−y}\)Al\(_y\)As barrier structures with rectangular barrier containing 50 period, weakly-coupled MQWs (\( L_w = 65 \) Å, \( L_B = 95 \) Å) was attributed to the ground state SRT [1,5,6].

For the sample with \( N_w = 4 \), however, the probability of ground state SRT through region II is negligibly small, due to the much thicker barrier (\( L_B = 310 \) Å) between the wells. In other words, the ground state SRT contribution to the dark current in this sample can be neglected. As a consequence, the electrons are expected to accumulate in the first quantum well of region II, leading to an increase in the effective Fermi level and hence to a decrease in the effective barrier height (see also [14]). Nevertheless, if the temperature is high enough, the electrons accumulated in the first quantum well can contribute to vertical transport by thermionic emission. As the applied voltage is increased further, the downward bending of the conduction band-edge of the barriers between the wells increases so that the electrons can undergo F–N tunnelling through the adjacent triangular potential barrier. The onset of F–N tunnelling through region II is expected to decrease the effective barrier height. Some of the electrons drifting in the conduction band of the barrier layers between the wells can be captured by the forthcoming quantum well(s). The electrons trapped in the last (4th) quantum well can undergo F–N tunnelling through the graded barrier (region III) and reach the anode. This argumentation explains the decrease of the effective barrier height with a progressively decreasing slope as the voltage applied to the sample with \( N_w = 4 \) is increased (Fig. 8). Accordingly, the essentially constant current in the initial part \( (T < 40 \) K) of the \( I–T \) curve at 0.7 V for the sample with \( N_w = 4 \) (see Fig. 2(c)) can be attributed to F–N tunnelling. The dark current measured at voltages lower than about 0.5 V is thermally activated in origin, and is controlled by the flow of electrons above the barriers and by the emission and trapping of electrons in the wells. Bishop et al. [14] noted, without presenting experimental data, that the measured barrier height for their sample with \( N_w = 4 \) decreased as the applied bias is increased. They argued that this was possibly caused by a build-up of electrons in the first quantum well, which were unable to tunnel out of the well.

Pelver et al. [7] observed constant dark current (for \( T < 65 \) K) in rectangular barrier samples with 50 period MQWs (\( L_w = 40 \) Å, \( L_B = 300 \) Å). They attributed the decrease of the measured barrier height with applied voltage to the F–N tunnelling which occurred at high voltage. Deng et al. [9] investigated the dark current in QWIP structures containing 30 period GaAs/Ga\(_{1−y}\)Al\(_y\)As (\( y = 0.25 \)) MQWs (\( L_w = 40 \) Å, \( L_B = 500 \) Å). They also concluded that the dark current at high bias voltage and low temperature was dominated by F–N tunnelling.
In some previous studies, the decrease of barrier height with applied voltage for GaAs/Ga$_{1-y}$Al$_y$As rectangular barrier structures containing no quantum wells [31–33] and 41 period MQWs ($L_W = 55$ Å, $L_B = 346$ Å) [34] was attributed to Poole–Frenkel effect [22,25]. The Poole–Frenkel effect is known as field-assisted thermal activation of electrons trapped on defects located in the barrier into the conduction band, and its presence in a barrier structure is characterised by the following two attributes [31–33]. (i) The barrier height obtained from $I–T$ measurements at low electric field should be lower than that ($\Delta E_c - E_F$) expected theoretically, and (ii) the barrier height should decrease linearly with $F^{1/2}$, where $F$ is the applied electric field. In the present study, we found that negative space charge was formed only in the sample with $N_w = 0$; however, the total barrier height of this sample decreased approximately linearly with the square of the applied voltage (Fig. 4). In addition, the total barrier height, determined from the $I–T$ curve measured at 0.01 V, was substantially larger than $\Delta E_c - E_F$. Although the effective barrier heights determined at 0.01 V for the samples containing $N_w = 4, 7$ and 10 quantum wells were comparable to $\Delta E_c - E_F$, the effective barrier height did not decrease linearly with $F^{1/2}$ (Fig. 8). Therefore, the results obtained for all barrier structure samples investigated in the present study do not exhibit any feature that is characteristic to the Poole–Frenkel effect.

5. Conclusions

The vertical current in GaAs/Ga$_{1-y}$Al$_y$As barrier structures with graded barriers between the $n^+$-GaAs contacts and the central barrier containing $N_w (=0, 4, 7$ and 10) quantum wells was measured in the dark as a function of temperature in the range 3.5–295 K, at selected applied voltages from 0.01 to 0.7 V. The results can be summarised as follows:

(i) Thermionic emission is the major vertical transport mechanism in all the samples at low voltage ($\leq 0.2$ V), regardless of the number of quantum wells.

(ii) The total barrier height of the sample with $N_w = 0$ decreased with applied voltage due to the voltage-induced decrease of the slope of the conduction band-edge of the graded barrier. The approximately constant dark current, at low temperatures ($< 20$ K) and high voltage ($\geq 0.3$ V), is ascribed to Fowler–Nordheim tunnelling.

(iii) The effective barrier height of the samples with $N_w = 7$ and 10 initially decreased with increasing applied voltage, and showed a tendency to saturate for voltages $\geq 0.2$ V. The temperature-independent dark current measured at low temperature ($< 80$ K) and high voltage ($\geq 0.3$ V) is attributed to ground state sequential resonant tunnelling through the quantum wells and Fowler–Nordheim tunnelling through the graded barriers.

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References