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Thermionic emission perpendicular to bulk and multiquantum $Al_xGa_{1-x}InP$ barriers

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A study on thermally activated currents across the bulk and multiquantum barrier (MQB) $Al_xGa_{1-x}InP/GaInP$ has been carried out and compared to experimental results from a series of n-i-n diodes over a range of temperatures. By considering the true quantum mechanical nature of the barriers, in contrast to the classical Richardson formalism, it is found that the alloy crossover strongly affects the transport properties of the material. The measured prefactor is found to decrease as Al content is increased. When applied to the MQB structures, the existing model fails to capture the experimental results. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2181648]

Semiconductor barriers, created by the conduction band offset at the heterojunction between two different materials, are commonly found in many devices, and determine the operating characteristics of such devices. For $Al_xGa_{1-x}InP/GaInP$ heterojunctions, as found between the active and cladding layers in a laser diode, the conduction band offset, ΔE_C, is relatively small (171 meV for $x=0.4$).[1] The existence of this small barrier means that electron leakage due to thermally activated electrons is a concern in the design and operation of efficient AlGaInP laser diodes. Several techniques have been proposed to suppress this leakage, including the multiquantum barrier (MQB).[2] This structure consists of a finite superlattice, preceded by a thick barrier. Constructive interference of the electron wave function in the superlattice results in enhanced reflectivity, while the thick layer acts to prevent low-energy electron transmission. While the incorporation of MQBs into devices has resulted in improved performance,[3,4] there is no definite experimental evidence that the MQB effect exists.

The thermally activated current density, J, can be described by the classical Richardson equation

$$J = A^* T^2 \exp\left(-\frac{\Delta^*}{k_B T}\right), \tag{1}$$

where $k_B T$ is the thermal energy, Δ^* is the barrier height, and A^* is the Richardson constant which is given by $em^* k_B^2/2\pi^2\hbar^3$, where m^* is the effective mass in the contact material.[5] This classical thermionic approach has been successfully used in determining the conduction band offset present at $Al_xGa_{1-x}InP/GaInP$ junctions for various alloy compositions.[6] However, there are two areas of concern regarding this approach. First, the equation is based upon a classical barrier, i.e., the transmission is zero for all $E<\Delta^*$, and it is transparent for all $E \geqslant \Delta^*$. However, when thin barriers are under consideration, this will obviously not be the case. Second, in this formalism A^* remains constant, regardless of the barrier composition under consideration. This is in contrast to experimental results from direct and indirect AlGaAs.[7]

In this letter, the thermal activation of carriers over single potential barriers and MQBs is studied both experimentally and theoretically. A range of bulk and MQB $Al_xGa_{1-x}InP/GaInP$ n-i-n diodes was fabricated incorporating a range of alloy compositions and dimensions. $Al_xGa_{1-x}InP$ is a direct (Γ-Γ) band gap material for $x<0.53$, and becomes indirect (Γ-X) as the Al composition is increased.[8] As a result, the nature of the transport between AlGaInP and GaInP should also change. The change in the band gap and electron effective mass is included in our calculations. Furthermore, consideration of the true transmission profile includes the quantum nature of the barriers. This allows for the tunneling of low-energy electrons through the barriers as well as introducing a lower than unity probability of the electrons surmounting the barrier. The transmission profiles of various bulk barriers and the more complicated MQBs are used in order to achieve a better understanding of thermionic transport in this material.

The current density perpendicular to a barrier surrounded by two thick contact layers is given by

$$J = \frac{em^* T}{2\pi^2\hbar^3}\int_0^\infty t(E) \ln\left[\frac{1+\exp(-E/k_B T)}{1+\exp(-E-eV/k_B T)}\right] dE, \tag{2}$$

where E is the electron energy, V is the applied voltage, and $t(E)$ is the transmission coefficient of the barrier.[9] This is calculated by means of a transmission matrix method (TMM), and incorporates the electron effective mass in the barrier material as well as that of the contact material. In this approach, $t(E)$ is determined by matching Ψ and $(1/m^*)\partial\Psi/\partial z$ at the barrier interfaces in order to maintain current continuity, and is calculated at zero bias. When the material is direct, the effective mass is given by $(0.11+0.24x)m_0$, and when indirect the values are obtained by interpolation from the ternaries.[10] The effective mass value in the GaInP contact layer is taken to be $0.11m_0$. The potential barrier heights were determined using a conduction/valence band offset split of 70:30.[1] Previous work in this material has indicated that an applied nonzero bias on the order of 10–40 mV is required to successfully use a thermionic emission analysis in determining the conduction band offset.[6] Exceeding these biases results in a current that is no longer dominated by thermionic emission, but instead contains components due to tunneling and other processes.

All n-i-n diodes tested were fabricated on n-type GaAs substrates by metalorganic vapor phase epitaxy. Each sample consists of a 0.2 μm n-GaAs buffer layer, 0.05 μm n

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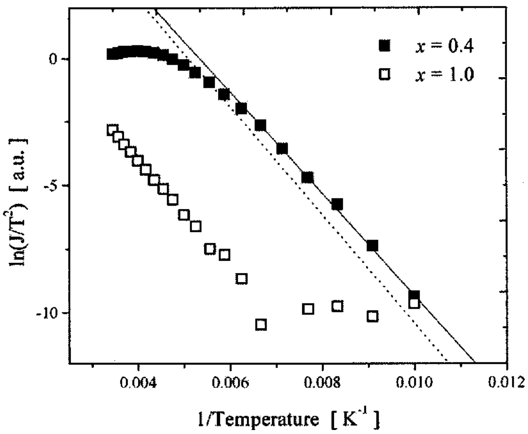

FIG. 1. Experimental thermionic currents for 40% and 70% bulk barriers at a bias of 30 mV. Also shown are the predicted currents as a solid and dashed line, respectively.

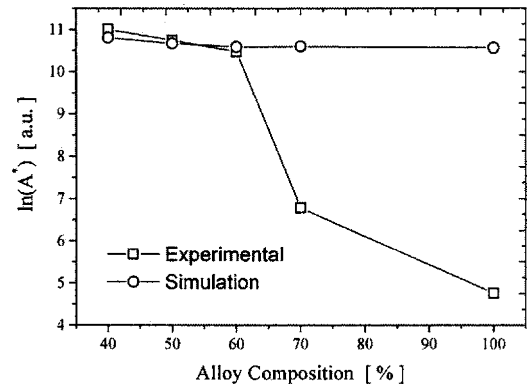

FIG. 2. Experimental and predicted ordinate prefactors for the bulk barriers as a function of alloy composition.

-$Ga_{0.5}In_{0.5}P$, 0.05 μm intrinsic $Ga_{0.5}In_{0.5}P$ spacer layer, an intrinsic bulk or MQB layer, a 0.05 μm intrinsic $Ga_{0.5}In_{0.5}P$ spacer layer, 0.05 μm n-$Ga_{0.5}In_{0.5}P$ layer, and a 0.2 μm n-GaAs capping layer. In the bulk barrier diodes, the $(Al_xGa_{1-x})_{0.52}Ga_{0.48}P$ was 1000 Å thick, and the alloy composition varied as $x=0.4, 0.5, 0.6, 0.7$, and 1. In the diodes containing an $Al_{0.4}Ga_{0.6}InP$/GaInP MQB structure, the initial layer was 180 Å wide, and was followed by five well/barrier pairs, whose widths varied from 14 to 32 Å in 2 Å increments. In these samples, the quasi-Fermi level lies within 20 meV of the conduction band edge in GaInP. A closed cycle cryostat was employed to allow the collection of I-V data over a temperature range of 20–300 K. Temperature feedback was via a T-type thermocouple and controlled to within ±0.5 K by a Eurotherm 2216e temperature controller. A Keithley 2400 source meter was employed to bias the diodes and measure current. All instruments were controlled and monitored via custom software designed using Agilent VEE.

In order to compare the simulation results with the experimental data, plots of $\ln(J/T^2)$ vs $1/T$ are formed. The slope of the linear portion in a theoretical plot is related to the activation energy, Φ, and the ordinate intercept yields the prefactor A^{**}. These are distinct from the conduction band offset Δ^*, and the Richardson constant, A^*, respectively. When the slopes are extracted from such plots, the predicted activation energies are found to be in agreement with the true values for all bulk compositions. However, there are variations in the values determined for the prefactors. In Fig. 1, the experimental and predicted curves are illustrated for the 40% and 70% bulk barriers, at a bias of 30 mV, which was selected in accordance with the requirements to assume a dominant thermionic mechanism. Good agreement is evident for the $x=0.4$ barrier, as was also seen for $x=0.5$ and 0.6. When the composition was increased to 70% and 100%, the predicted thermionic curve, as shown by the dashed line, was found to be vertically displaced upwards from the measured data. The predicted value of this prefactor is close to that of $x=0.4$, yet the experimental data clearly show that this is not the case. For 70% and 100%, the predicted prefactor is found to be respectively approximately 55 and 400 times too large when compared to experiment.

The measured prefactors for the various compositions are compared to the predicted values in Fig. 2. The predicted values vary from 4.93 to 3.87 A cm^{-2} K^{-2}, while the measured values exist over a greater range of 5.93–0.012 A cm^{-2} K^{-2}. These are in contrast to the constant value of 13.2 A cm^{-2} K^{-2} given by the classical Richardson equation. (All prefactor values given here are scaled by m^*/m_0.) The measured values are observed to coincide with the predicted values up to the indirect composition of $x=0.6$. Once x increases beyond this value, the measured prefactors deviate noticeably. The crossover point in this material occurs approximately at $x=0.53$, and the proximity of the 60% material to this point may explain the lack of deviation at this composition. These results exhibit a similar trend to those observed experimentally in AlGaAs.[7] Variations in the prefactor value have been found to be relatively insensitive to the value of the effective mass used, so lack of knowledge of m^* can be ruled out as the source of this discrepancy. The smaller experimental prefactors would indicate that within this model, the channel appears to be more transparent than shown by experiment, or that only a fraction of Γ-like waves incident on the barrier will be transported via the X channel. A possible explanation for this comes from the close relation of the prefactor to $t(E)$, which is determined by matching the envelope functions and their derivatives, thus neglecting the fast oscillating part of the wave function.

The transmission profile of the various direct band gap MQB structures as determined via the TMM were incorporated into Eq. (2) in order to calculate the thermionic current across the devices. The activation energies extracted from $\ln(J/T^2)$ vs $1/T$ plots predict the existence of an enhanced barrier, which is greater than the conduction band offset present at the junctions. However, the barrier heights extracted from the experimental data do not agree with prediction, as shown in Fig. 3. The thermionic method predicts enhancements of over 100 meV from the bulk value of 171 meV, while the experimental measurements show no significant enhancement. This discrepancy most likely arises from the fact that the TMM predicts a barrier enhancement, which is then carried into the thermionic calculations. The predicted A^{**} values for the MQB structures ranged from 2.71 to 0.34 A cm^{-2} K^{-2}, which are smaller than that measured for the 40% alloy. This is likely due to the compound structure of the diode. As the MQB structures possess thinner barriers than those of the bulk diodes, it is likely that considering the electron transport to be entirely due to thermionic emission is incorrect. Other mechanisms, such as Fowler-Nordheim tunneling or Poole-Frenkel emission, may

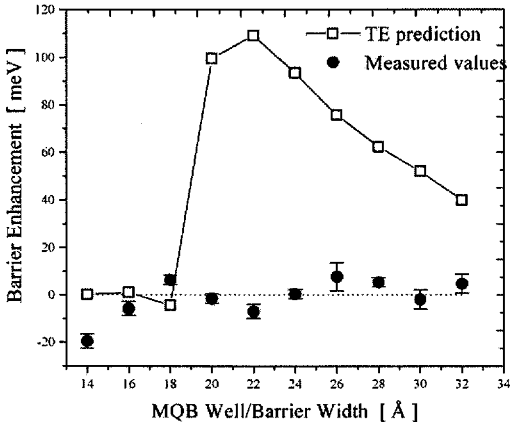

FIG. 3. Predicted activation energy enhancements and experimentally determined values for MQB structures of varying dimension. The dashed line represents zero enhancement over the bulk case.

be taking place, thus reducing the barrier height measurement as determined by a thermionic analysis.

In conclusion, the thermally activated current across AlGaInP bulk barriers and MQBs has been calculated for various aluminium compositions and for differing thicknesses by including the quantum mechanical nature of the barriers. It is found that while this method returns an activation energy close to conduction band offset for bulk barriers, the ordinate prefactor does not remain constant over the bulk composition range, and that the measured values differ from the classical constant value. In the MQBs, the model fails to capture the experimental results observed.

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