Critical state alignment and charge accumulation in triple barrier resonant tunnelling structures

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ABSTRACT

We report observations of resonant tunnelling features in the current-voltage (I(V)) characteristics of a series of triple barrier resonant tunnelling structures (TBRTS) due to the critical alignment of the n=1 confined states of the two quantum wells within the active region. Charge accumulation in the first QW of these structures has a significant effect on the I(V) characteristics of the resonances. A nominally symmetric TBRTS and asymmetric TBRTS, with decreasing second well widths, have been studied, with observations of charge accumulation affecting the critical alignment in both symmetric and asymmetric designs.

We demonstrate that in highly asymmetric structures the critical alignment can occur coincident to the Fermi level in the emitter, and remains on resonance at higher bias than is expected due to charge accumulation in the structure.

With great renewed interest in tunnelling structures for high frequency (THz) operation, the understanding of device transport and charge accumulation is critical.

1. INTRODUCTION

Semiconductor multi-barrier tunnelling structures, where the quantum well (QW) confined states are strongly coupled, have attracted considerable interest over a number of years for both fundamental investigations of tunnelling processes and electronic and optoelectronic applications. It has been proposed that quantum oscillations in resonant tunnelling structures can be utilised in devices which can be operated at terahertz frequencies [1]. Multi-barrier ($\geqslant$ 3) tunnelling structures have been proposed to overcome some of the problems limiting the ultimate frequency of oscillation suggested in reports of conventional double barrier resonant tunnelling structures (DBRTS) [2], but recent reports of measured THz operation in DBRTS have proved the pessimism concerning the maximum oscillation frequency to be unfounded [3]. It was demonstrated that the resonant features in the I(V) characteristics of triple barrier resonant tunnelling structures (TBRTS) may be stronger than those observed in the more widely studied DBRTS [4,5]. In TBRTS transmission through the device is strongly controlled by the 2D to 2D state alignment and so there is an effective suppression of the off resonant current. Proper design of TBRTS where the 2D to 2D state alignment occurs coincident to the Fermi level, will allow for large peak to valley current ratios necessary for efficient high speed devices.

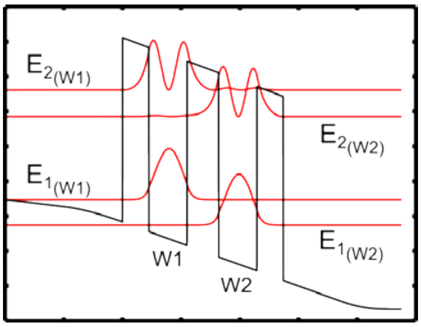

Figure 1. Conduction band potential profile for a symmetric structure under bias. The electron probability density shows the n=1 states are misaligned and localized to a specific quantum well ($E_{1(W1)}$ for W1 and $E_{1(W2)}$ for W2).

2. EXPERIMENTAL DETAILS

The symmetric barrier TBRTS with either symmetric or asymmetric QW's were grown by solid source molecular beam epitaxy on semi-insulating GaAs substrates, the active region comprised of the following layers:

i) 45 Å $Al_{0.33}Ga_{0.67}As$ barrier,
ii) Nominally 65 Å undoped GaAS quantum well,
iii) 54 Å $Al_{0.33}Ga_{0.67}As$ barrier,
iv) Undoped GaAs quantum well of nominal widths 45, 48, 51, 54, 57, 59, 62 Å for the asymmetric QW devices, and 65 Å for the symmetric QW device,
v) 45 Å $Al_{0.33}Ga_{0.67}As$ barrier,

Device structures were fabricated by conventional photo-lithography into 50×50 µm mesas and top and bottom AuGe/Ni/Au ohmic contacts formed. Current-voltage (I(V)) characteristics were measured using a four wire technique. A conduction band potential profile for a symmetric structure calculated from a self-consistent Schrödinger-Poisson model is shown in Fig 1. along with the calculated electron probability density for the lowest significant confined states.

3. RESULTS AND DISCUSSION

I(V) characteristics for a series of increasingly asymmetric devices at 121K, where the second QW width is reduced by approximately a monolayer for each sample are shown in Fig 2. A resonant current peak at point (i) is

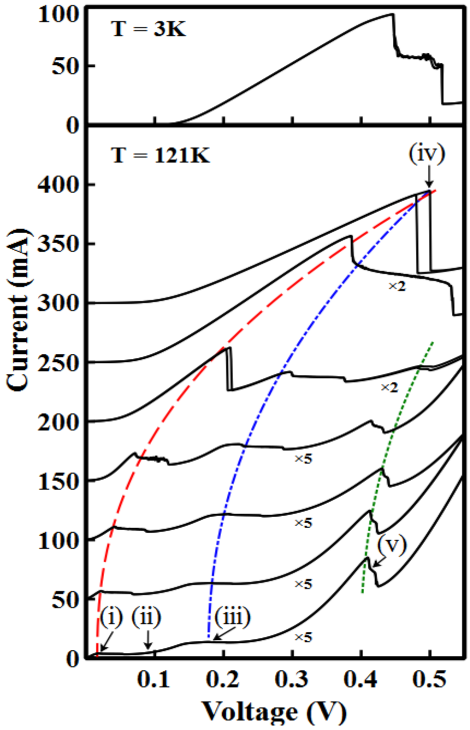

Figure 2. Current-Voltage (I(V)) characteristics for a range of increasingly asymmetric QW TBRTS at 121K. I(V) characteristics for different structures are offset by 50 mA for clarity. Lines are shown to guide the eye to the evolution with increased TBRTS asymmetry of the thermally activated (dashed line) and non-thermally activated (dashed-dotted and dotted) peaks. The peaks assigned by points (i), (ii), (iii), (iv) and (v) are discussed in the main body text. The 3K I(V) characteristic for the most asymmetric device is also shown. The large single peak at low temperature suggests the alignment of the QW states is virtually coincident with the Fermi energy in the emitter.

seen at low bias. This is attributed to the critical alignment of the two n=1 QW states ($E_{1(W1)}$ and $E_{1(W2)}$) [6]. A small region of negative differential resistance (NDR) can be seen and becomes more pronounced as the asymmetry of the structure is increased and results in instabilities in the NDR region. With increasing structure asymmetry the peak occurs at increasingly higher bias. This reflects the increased bias required to align the n=1 QW states as the confinement energy of the second well state increases when the well width is decreased. This peak also becomes discernable at lower temperatures as asymmetry is increased as the QW state alignment occurs at energies closer to the Fermi level in the emitter region.

A small peak at (ii) is discernable at low temperatures, but becomes concealed by thermal leakage as temperature is increased. This resonance is attributed to alignment of the n=1 QW state $E_{1(W1)}$ and the populated 3D states in the emitter region $E_{M(3D)}$. The alignment of the QW state $E_{1(W2)}$ and the populated 3D states in the emitter region $E_{M(3D)}$ also occurs and is labelled (iii) in figure 2. This peak exhibits a region of NDR and instability and remains on resonance over a larger bias range that would necessarily be expected. This is attributed to charge accumulation in the first QW [7]. This feature remains pinned on resonance; with charge accumulating in the first quantum well, until alignment occurs with the second QW n=2 state $E_{2(W2)}$ shown at point (v). The structure and small NDR region seen at (iii) is attributed to a transition between a 3D and a 2D emitter state. Feature (iii) remains relatively stable in voltage as structure asymmetry is increased until it begins to merge with features (i) and (ii) at point (iv). It is here where the alignment of the n=1 QW states, $E_{1(W1)}$ and $E_{1(W2)}$ occur coincidentally with the populated 3D emitter $E_{M(3D)}$. This can be seen in Fig 2. for the case of the highly asymmetric structure at 3K. The proximity of the Fermi level in the emitter with respect to the aligned QW states accounts for a large increase in the tunnelling current through the device at 3K. At this point the device can be considered as a conventional double barrier resonant tunnelling structure with a modified emitter that acts as an energy filter for injected electrons.

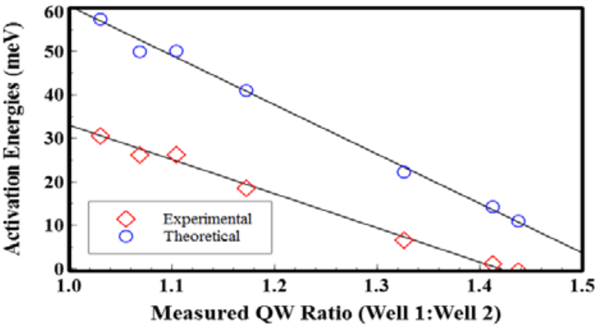

Figure 3. Theoretical and experimentally determined activation energies of n=1 critical alignment resonance vs measured QW ratio.

Figure 3 shows experiment and modelled activation energies for the critical state alignment as a function of structure asymmetry. There is a discrepancy between the model predictions and the experimentally determined values as a result of charge accumulation. Alignment that relies on charge accumulation extending the peak resonance voltage by pinning as observed in the experimental results would be detrimental to high frequency operation due to capacitance associated with this charge.

4. REFERENCES

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