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MAGNETIC FIELD STUDIES OF NEGATIVE DIFFERENTIAL CONDUCTIVITY IN DOUBLE BARRIER RESONANT TUNNELLING STRUCTURES BASED ON n^-InP/(InGa)As

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ABSTRACT

Negative differential conductivity (NDC) with a peak/valley ratio of 4.5:1 (4 K) and 2:1 (150 K) is observed in double barrier resonant tunnelling devices based on n^-InP/(InGa)As. A transverse magnetic field applied in the plane of the tunnelling barriers ($\underline{J} \perp \underline{B}$) significantly changes the current-voltage characteristics and eliminates the NDC for fields above ~10 T. This behaviour is explained qualitatively in terms of the effect of the magnetic vector potential on the tunnelling electrons. The magneto-oscillations in the tunnelling current for $\underline{J} \parallel \underline{B}$ are discussed in terms of a simple model of resonant tunnelling.

KEYWORDS

Negative differential conductivity; resonant tunnelling devices; magnetotunnelling; (InGa)As/InP

Since the early work of Esaki and Tsu (1973) on double barrier resonant tunnelling devices there has been a recent resurgence of interest in this type of heterostructure. Most effort has concentrated on the GaAs/(AlGa)As heterostructure system (Sollner et al. 1983) but recently considerable progress has been made with (InGa)As/InP (Vuong et al. 1987) and (AlIn)As/(InGa)As (Inata et al. 1986). In this article, we report on the electrical properties, including magnetic field studies, of asymmetric double barrier structures based on (InGa)As/InP, grown by molecular beam epitaxy.

The structures consisted of layers with the following nominal dopings, in order of growth from the substrate: (1) n^+InP substrate; (2) 0.25 μm, n = 10^{18} cm^{-3} n^+ InP buffer; (3) 0.5 μm, 3 x 10^{17} cm^{-3} n^+(InGa)As; (4) 8.0 nm, nominally undoped InP; (5) 4.5 nm, nominally undoped (InGa)As; (6) 8.0 nm, nominally undoped InP; (7) 0.4 μm (InGa)As, $\lesssim 10^{16}$ cm^{-3} (8) 1 μm, 3 x 10^{17} n^+(InGa)As. Mesas of 100 μm diameter were etched using 1:1:1 of Hydrobromic acid : Acetic acid : Potassium dichromate by volume. No problems with surface conduction (Vuong et al. 1987) were encountered.

Figure 1 shows the current-voltage characteristics I(V) of a mesa of diameter 100 μm, taken at 4 K. A peak/valley ratio of 4.5:1 is observed in forward bias (substrate side biased positive). At 150 K the peak/valley ratio is 2:1. The other interesting feature of the I(V) curve is the asymmetry between forward and reverse bias. This reflects the different doping levels on either side of the double barrier. The effect of magnetic field on the tunnel current is shown in Figures 2 and 3.

Aside from the small notch around zero bias, the I(V) characteristics are almost ohmic in the low voltage region. According to the conventional model of resonant tunnelling this behaviour indicates that the lowest energy bound state of the quantum well is already overlapped by the electron energy distribution of the contact layers at V = 0. This means that resonant tunnelling takes place at arbitrarily small applied voltages. From the nominal doping and well thickness values of the structure we conclude that a considerable amount of positive space charge exists in the barrier and well regions. This has the effect of lowering the threshold energy for resonant tunnelling. It is noteworthy that in a structure with similar nominal dopings to those given above but with a narrower well width (3.7 nm), the low voltage impedance is considerably higher, i.e. a voltage of around 50 mV is required to switch on the resonant tunnelling process.

The fact that the current passed by the wider well (4.5 nm) structure is "resonant" even at very low bias makes it attractive from the viewpoint of studying resonant magnetotunnelling. In particular, we show that for this structure the period of the magneto-oscillations close to zero bias is given simply by the difference between the Fermi energy of the contact layer and the bound state energy of the well.

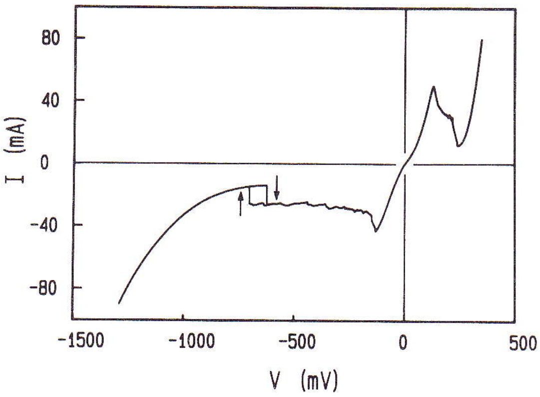

Fig. 1. The I(V) characteristics at 4 K of a double barrier structure in the form of 100 μm diameter mesa.

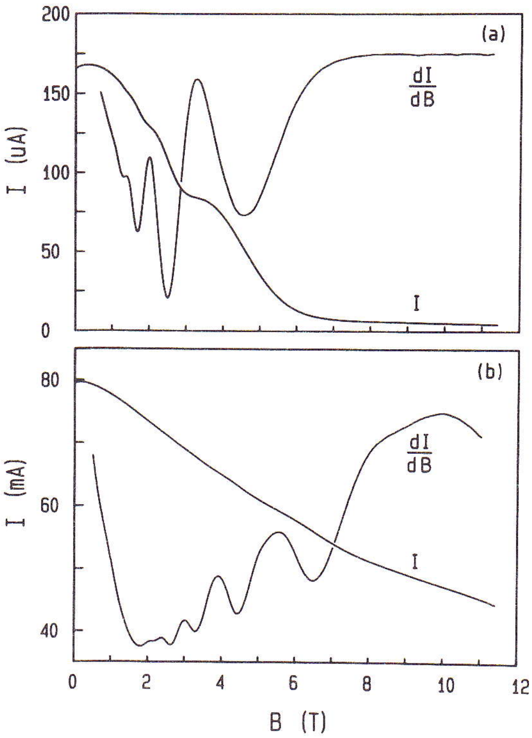

Fig. 2. The magnetotunnelling current I(B) and dI/dB for $\underline{B} \parallel \underline{J}$ at 4 K (a) V = 1 mV (b) V = 350 mV. The large difference in the periods of the oscillatory structure is clear.

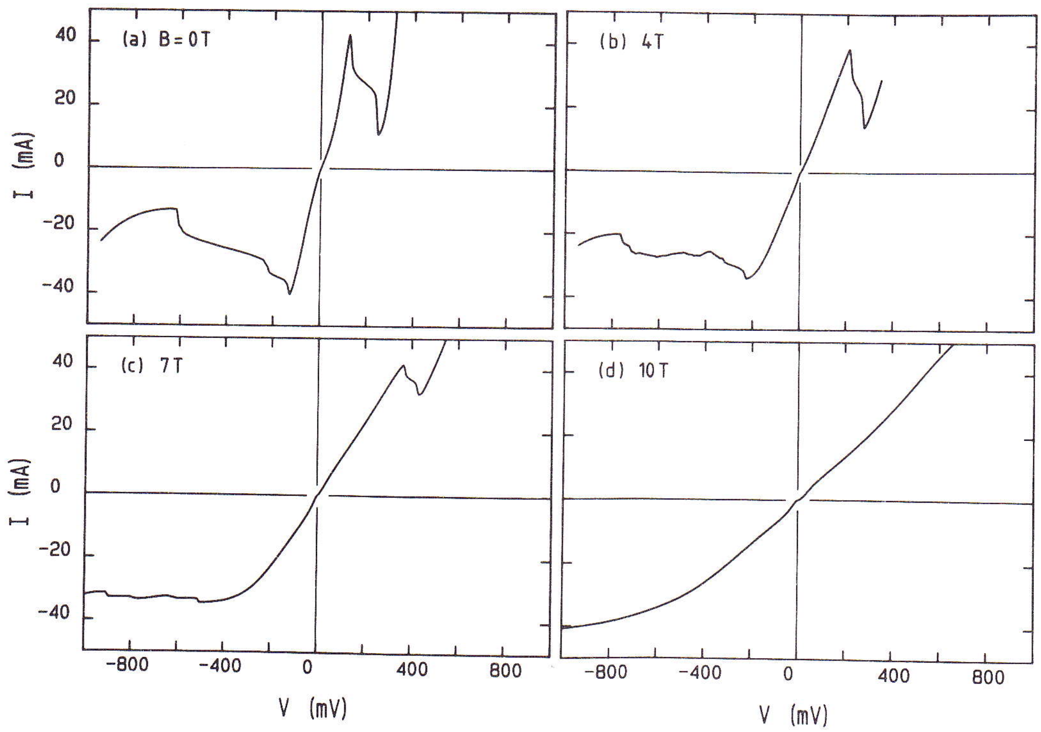

Fig. 3. The change of the I(V) characteristics in the presence of a transverse magnetic field $\underline{J} \perp \underline{B}$ at 4 K(a) B = 0 T (b) 4 T (c) 7 T (d) 10 T.

Typical curves of the magnetotunnelling current and the magnetotunnelling oscillations are shown in Figure 2 at low and high bias with $\underline{B}\|\underline{J}$. The oscillations show a characteristic periodicity in inverse magnetic field so that a fundamental field or inverse period $B_f = [\Delta(1/B)]^{-1}$ can be defined. At low bias (Figure 2a), the fundamental field is much lower than that observed at high bias (Figure 2b). The low bias oscillations have a clear two-dimensional character: by tilting $\underline{B}$, the magnetic field positions of the oscillations show a characteristic frequency shift, given by $B_f(\theta) = B_f\cos\theta$, where $\cos\theta = \underline{J}.\underline{B}/JB$. A remarkable feature of the low-bias current is that it is strongly suppressed by the magnetic field. This does not occur for tunnelling through a single barrier in the case of $\underline{B} \| \underline{J}$ (Eaves et al. 1987). The much higher frequency magneto-oscillations observed at high bias (350 mv) in the voltage range corresponding to off-resonant tunnelling are due to Landau level effects in the n^+(InGa)As contact layers. A detailed analysis of the magneto-oscillations over the full voltage range will be given in a subsequent publication.

The magneto-oscillations and suppression of the current at low bias can be understood in terms of the basic physics of resonant tunnelling through double barrier structures in the presence of a magnetic field (Sheard and Toombs, 1987). For $\underline{B} \| \underline{J} \| \underline{x}$, the electronic energy levels are of the form $E = E_x + (n + \frac{1}{2})\hbar\omega_c$ where E_x is the component of the energy for the x-direction perpendicular to the barriers, $\omega_c = eB/m$, m is the electronic effective mass for (InGa)As and all energies are measured relative to the conduction-band edge of the emitter. The energy E is conserved in the tunnelling process as are the wavevector k_y and Landau level quantum number n. Electrons can therefore only tunnel resonantly with $E_x = E_w$ where E_w is the bound-state energy in the well. If we assume that the broadening of the well-state energy is very much less than E_F, the Fermi energy of the emitter, electrons tunnel with a well-defined value of E_x. As can be seen from Figure 4, the number of electrons which can then tunnel from the emitter is

$$N_T = 2 \sum_{n,ky} f\{E_w + (n + \tfrac{1}{2})\hbar\omega_c - E_F\}$$

where f is the Fermi-Dirac distribution. N_T controls the tunnel current (the nett current is given by the difference between the rates of electrons tunnelling from the emitter and the collector) and the bias V determines $E_F - E_W$. N_T oscillates with B as the Landau levels pass through E_F as can be seen by reference to Figure 4. We take $E_F - E_W << E_F$ so that E_F can be considered constant for the fields of interest. The current will have an oscillatory structure, periodic in 1/B, and the fundamental field for the current oscillations is $B_F = m(E_F - E_W)/e\hbar$. Since $B_F = 5.5$ T, this shows that the well state is some 13 meV below the emitter Fermi energy at zero magnetic field and zero bias. If $\frac{1}{2}\hbar\omega_c > E_F - E_W$, there are no occupied states from which an electron can tunnel and the resonant current is totally suppressed. This result is in marked contrast to that for non-resonant tunnelling where electrons can tunnel with any value of E_x in the range 0 to E_F and there are always occupied states to tunnel from. The current should be suppressed for fields $B > 2B_F$, using our simple model. In practice, it is strongly suppressed for $B > B_F$. A possible explanation of this could involve the electrostatic feedback of the charge in the well.

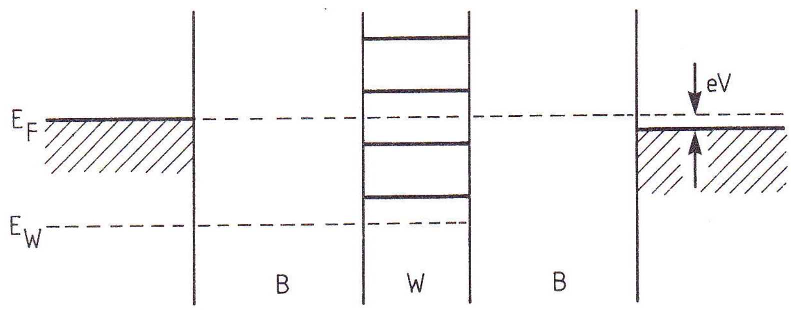

Fig. 4. Schematic diagram showing the Fermi levels in the emitter and collector for a bias V. The position of the well-state is also shown and the Landau levels are indicated by solid horizontal lines. B and W denote respectively the barriers and the well.

When a transverse magnetic field is applied to the device in the plane perpendicular to the current ($\underline{B} \perp \underline{J}$), the main features in the I(V) curve are observed to shift to higher voltages. At sufficiently large magnetic fields (B > 7 T) the features in the NDC region grow less prominent, the NDC finally becoming completely quenched for B > 10 T. This behaviour is shown in Figure 3 for the I(V) characteristics at fields of 0, 4, 7 and 10 T. Also evident in Figure 3 is that as B is increased the width (on the voltage axis) of the high impedance notch around zero bias increases. That is, the 'turn on' voltage at which the current increases moves to higher bias. Similarly, the sharp drop (cut-off in current) which occurs around 130 mV at B = 0 shifts to higher voltages with increasing magnetic field. These features can be qualitatively understood in terms of the Hamiltonian of the tunnelling electron in the presence of a magnetic field (Eaves et al., 1986, Davies et al., 1987). Assuming that the energy and canonical momentum are conserved in the tunnelling process, it can be shown that the changes in the turn-on and turn-off bias voltages are associated with the effect of the magnetic vector potential on the electrons tunnelling from essentially three dimensional electrons in the n^+ contact regions to the two dimensional states of the well. The changes are given by

turn-on voltage: $\Delta V_{on} = \frac{\hbar^2}{2me}(k_0 - k_F)^2$ for $k_0 > k_F$

and $\Delta V_{on} = 0$ for $k_0 < k_F$;

turn-off voltage: $\Delta V_{off} = \frac{\hbar^2}{2me}(k_0^2 + 2|k_F k_0|)$

In these equations, the ΔV refer to the change in the potential difference between the emitter Fermi energy and the conduction-band edge of the well, k_F is the Fermi wavevector of the electrons in the emitter contact, $k_0 = eB\Delta x/\hbar$ and Δx is the effective length over which the magnetic vector potential acts on the electrons. The above relationships provide a qualitative understanding for the change in the I(V) characteristics with increasing magnetic field ($\underline{B} \perp \underline{J}$), in particular the way in which the turn-on and turn-off features in the I(V) curves move to higher bias with increasing B. The suppression of the NDC by the magnetic field can also be understood in terms of the action of the magnetic vector potential on the electrons in the emitter contact which have a spread in their canonical momentum given by the Fermi energy of the contact.

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