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GaAs/(AlGa)As/GaAs/(AlGa)As/ n^+ GaAs
RESONANT TUNNELLING DEVICES USING HIGH
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INVESTIGATIONS OF THE NEGATIVE DIFFERENTIAL CONDUCTIVITY AND CURRENT BISTABILITY IN DOUBLE BARRIER n^+ GaAs/(AlGa)As/GaAs/(AlGa)As/ n^+ GaAs RESONANT TUNNELLING DEVICES USING HIGH MAGNETIC FIELDS

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Conductivité négative différentielle (CND) et bistabilité en courant dans une structure tunnel résonnante ont été étudiées par l'effet oscillatoire dans le courant magnétotunnel avec $J \parallel B$. Les mesures montrent que la bistabilité est associée avec l'accumulation et l'éjection de charge négative du puits. CND associé avec la deuxième sous-bande du puits est observée à plus grand voltage (~ 1 V). Les magnéto-oscillations indiquent la présence du tunnel séquentiel à cette région.

Negative differential conductivity (NDC) and current bistability in a resonant tunnelling device are investigated by examining the oscillatory structure in the magnetotunnelling current for $J \parallel B$. The data support the conclusion that bistability is associated with build-up and ejection of negative space charge from the well. The charge density of 2D electrons in the contact accumulation layer is measured directly. NDC due to tunnelling into the second sub-band of the well is observed at high bias (~ 1 V). The associated magneto-oscillations indicate the presence of sequential tunnelling in this region of the $I(V)$ curves.

Resonant tunnelling devices (RTD) based on double barrier semiconductor heterostructures exhibit a range of interesting physical properties: negative differential conductivity (NDC); high frequency oscillations [1]; current bistability [2,3]; band structure effects [4]; magnetoquantum effects [5]. In addition, they have stimulated considerable theoretical discussion [6-8]. The band diagram is shown schematically in Figure 1. The structures were grown at Nottingham by MBE using a Varian GEN II and comprised layers with the following thicknesses and nominal dopings: n^+ GaAs substrate, $2 \times 10^{18} \text{ cm}^{-3}$; n^+ GaAs buffer layer, $2 \times 10^{17} \text{ cm}^{-3}$, $1 \mu\text{m}$; (AlGa)As barrier, [Al] = 0.33, width $b = 8.8 \text{ nm}$; undoped GaAs well, $w = 5.6 \text{ nm}$; (AlGa)As barrier, [Al] = 0.33, 8.8 nm ; n^+ GaAs top layer, $2 \times 10^{17} \text{ cm}^{-3}$, $1 \mu\text{m}$.

The $I(V)$ characteristics shown in Figure 2 exhibit pronounced NDC with peak-to-valley ratio of up to 16:1 at 4 K (10:1 at 77 K). There is also pronounced current bistability over certain voltage ranges. The NDC and associated bistability below ~ 0.4 V are very similar to those reported recently [3]. The rise in current as V is increased to 159 mV is attributed to tunnelling of bulk electrons into the lowest quantum well state. The sharp fall-off and bistability beyond the peak are attributed to ejection of electrons from the well [3]. In addition, however, we observe a further region of NDC at higher voltage (~ 0.9 - 1.2 V). When a magnetic field, B , is applied perpendicular to the barriers ($J \parallel B$), well-resolved Shubnikov-de Haas-like (SdH) oscillations, periodic in $1/B$, are observed under constant voltage conditions over almost all of the voltage range. The oscillations can be seen in the direct $I(B)$ curves but are considerably

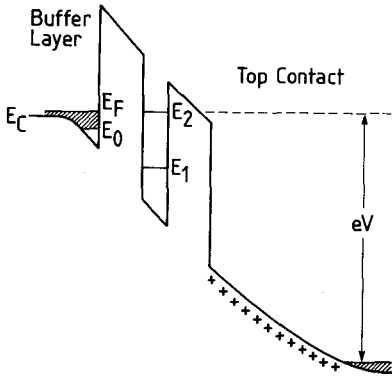


Figure 1 Schematic band diagram of device under large forward bias in the absence of charge in the well. The bias corresponds to that part of the $I(V)$ curve (~ 0.6 V) near the onset of resonance between the occupied conduction band levels of the buffer layer and the second sub-band (E_2) of the quantum well.

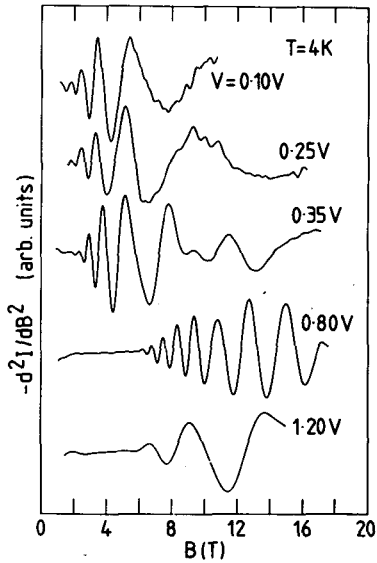


Figure 3 Second derivative of $I(B)$ showing the changing nature of the magneto-oscillations at various parts of the $I(V)$ curve.

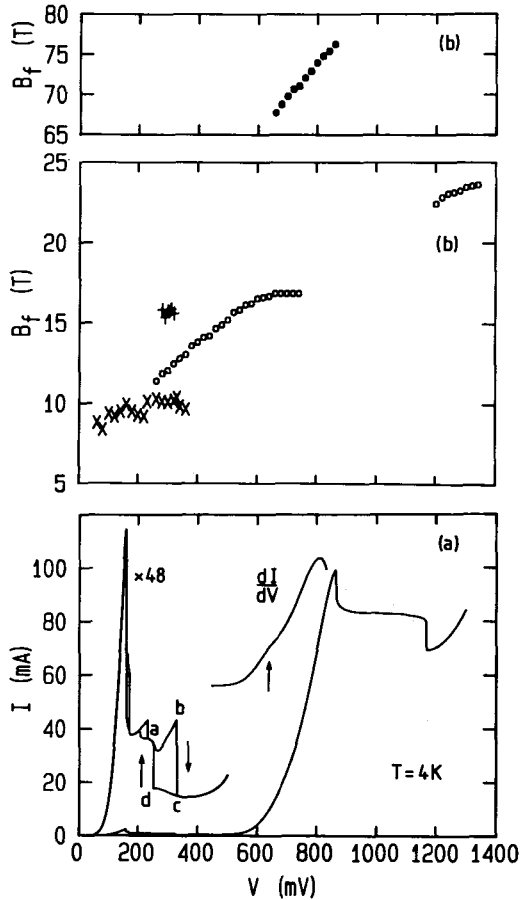


Figure 2(a) Four-terminal $I(V)$ characteristics of device at 4 K with negative substrate bias. The low voltage part is magnified $\times 48$. The conductance near 0.6 V is also shown. **(b)** Fundamental fields, B_f , versus bias for the magneto-oscillations in different regions of the $I(V)$ curve. The $I(V)$ curves are for a mesa with 200 μm diameter.

enhanced in the derivative plots, d^2I/dB^2 . Similar oscillations have been observed and interpreted in magnetotunnelling measurements on single barrier structures [9]. Typical curves are shown in Figure 3 for various applied voltages at 4 K. Each series of oscillations can be defined by a fundamental field or inverse period $B_f = [\Delta(1/B)]^{-1}$. These are plotted in Figure 2b.

We employ this oscillatory structure to investigate the resonant tunnelling and the location and magnitude of space charge in the various parts of the device under operating conditions. At low bias, (< 60 mV, substrate negative), rotation of the magnetic field relative to the plane of the barrier indicates that the oscillatory structure has more of a three-dimensional character than two-dimensional. The fundamental field $B_f = 9$ T gives a bulk electron density of $1.6 \times 10^{17} \text{ cm}^{-3}$, close to the nominal contact doping value. As V is increased towards the first peak at 159 mV, B_f increases slightly to around 10 T. Around the resonance, the oscillations appear to develop a 2D character: by tilting B , the oscillations show a characteristic frequency shift, given approximately by $B_f(\theta) = B_f/\cos\theta$, where $\cos\theta = J_B/JB$. This behaviour presumably reflects the nature of the quantised bound state of the well [5]. The sharp fall-off in current and the narrow region of bistability beyond this peak have been attributed to ejection of electrons (negative space charge) from the well [3]. In the second region of bistability (abcd), it is generally possible to obtain clear SdH oscillations in both the high and low current modes. On the curve (a**) (high current mode of bistability), oscillations corresponding to $B_f = 10$ T are still clearly observed (indicated by x). Superimposed on these is a second series with $B_f = 16$ T (indicated by +) in a narrow region from 280 to 320 mV. In the low current mode (c**d**) a single series of peaks is observed with a B_f (indicated by o) which increases gradually with bias. This series is clearly observed for voltages (≤ 740 mV) well into the monostable region. By tilting B , these oscillations show a very clear 2D character. We attribute this series to the Landau level structure of the degenerate two-dimensional electron gas (2DEG) in the accumulation section of the buffer layer (Figure 1). For the accumulation layer, B_f is related to the 2D carrier density by $n_{2D} = 2eB_f/h$. This therefore allows us to calculate the accumulated charge and the associated electric fields and potential differences throughout the device. Similar oscillations, also of 2D character and attributable to the 2DEG in the accumulation layer of the buffer contact, are observed at higher bias (> 1.20 V). Assuming that the applied voltage V is associated only with this negative space charge in the accumulation layer (given by B_f) and with the positive space charge due to ionised donors (N_{Dt}) in the depletion layer of the top contact, it is easy to show that for a sufficiently accumulated layer**

$$V = (2b + w + \ell_1)(2e^2/h\epsilon\epsilon_0)B_f + B_f^2(2e^2/h)/(2N_{Dt}e\epsilon\epsilon_0). \quad (1)$$

Here ℓ_1 is the stand-off distance from the barrier of the 2DEG in the accumulation layer. A term for the charge in the well can also be included. When comparing the B_f in Figure 2b with the $I(V)$ in Figure 2a, the region of bistability abcd is particularly noteworthy. The B_f values (o) in the low current region cd are significantly larger than those (10 T, marked x) of the dominant oscillatory series in the high current mode. This indicates that in the high current (ab) mode the buffer region adjacent to the barrier is less strongly accumulated than in the low current mode (cd). These observations offer support to the model for the bistability given in [3]. At the sharp transition b**c**, negative space charge is released from the well, thus increasing accumulation in the buffer layer and giving rise to the observed increase in B_f in the low current mode at c. Note in the low current mode c**d**, the accumulation remains at this higher level, indicating a much lower level of electron space charge in the well. Equation (1) gives a reasonable fit to the oscillations associated with the accumulated 2DEG (denoted by o in Figure 2b) for voltage above ~ 400 mV. The fit is particularly good for the oscillations above 1.20 V, which we also attribute to Landau level effects in the accumulation layer. We speculate that the second series with $B_f = 16$ T in the high current mode may be related to Landau levels of the E_1 subband in the well.

At intermediate voltages (660-860 mV), near the principal peak in the current, an additional series of oscillations is observed with very high $B_f \approx 70-80$ T, as

shown in Figure 2b (indicated by ●). These also have two-dimensional character. They cannot be explained in terms of Landau level structure passing through an equilibrated Fermi energy since the associated electron sheet density would give rise to electric fields much too large to be consistent with the applied voltage. We attribute the peak in the current at 880 mV to resonant tunnelling from the bound state of the accumulation layer E_0 into the second bound state of the well E_2 (see Figure 3). At this resonance ($E_2 \approx E_0$) an appreciable density of electrons builds up in the well. This is evident from the flattening off of the B_f -values (17 T) of the accumulation layer series (o) between 600 and 740 meV. We thereby estimate that the electron density in the well builds up to around $1 \times 10^{11} \text{ cm}^{-2}$ at the 880 mV peak. The resonant state E_2 is overlapped in energy by the higher n Landau levels of the lower well state E_1 . Intersubband scattering processes (impurities, electron-electron, phonons) can transfer electrons out of the E_2 resonance into these Landau states. For elastic tunnelling and (quasi-) elastic scattering processes, scattering will be a maximum when

$$E_1 + n \frac{\hbar e B}{m^*} = E_0 \approx E_2, \quad n = \text{integer.}$$

This gives rise to oscillatory structure (2D in nature) with $B_f = (E_0 - E_1)m^*/\hbar e$.

A simple estimate of $(E_0 - E_1)$ from the potential profile in the device (see Figure 3) at an applied voltage around 0.8 V gives a value of $B_f = 90 \text{ T}$, in reasonable agreement with that observed. Note that as V is increased, $E_0 - E_1$ will also increase, but rather slowly, as is observed, due to the build-up of negative charge in the well. A process of the type proposed would modulate the current as a function of B since transfer of electrons from E_2 to E_1 modifies the tunnelling probability and electron space charge density in the well. To conclude this section, it is worth noting that the dI/dV curve shows a weak feature around 0.6 V due possibly to the resonance between E_2 and the conduction band edge of the buffer contact.

Our observation of the high B_f series and its interpretation imply that the tunnel current near the $E_0 - E_2$ resonance involves, at least partially, electrons which are undergoing intersubband scattering in the well, i.e. they are tunnelling sequentially [6,7]. The mechanism which we propose is quite distinct from the one described in reference [5] which relates to bulk (3D) electrons tunnelling into E_1 in the presence of a quantising $B \parallel J$ and for which Landau level number n and k are conserved.

Finally, we note briefly that for $B \perp J$, the NDC is partially suppressed at high magnetic fields ($B > 5 \text{ T}$). In addition, the resonant structure shifts to higher voltage. Both features can be explained by including the effect of the magnetic vector potential on the electron Hamiltonian.

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