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LETTER TO THE EDITOR

Ballistic transport in resonant tunnelling devices with wide quantum wells

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Abstract. Resonant tunnelling is investigated in double-barrier devices based on n-GaAs/(AlGa)As. The central GaAs wells have widths of 60, 120 and 180 nm. The 60 nm wide well exhibits 18 clear quantum resonances in the conductance even at room temperature. At low temperatures, over 70 resonances are observed for the 120 nm well device. The amplitudes of the resonances are found to be modulated by a quantum interference effect involving the collector barrier. The electron traversal time across the well is typically 0.1 ps, corresponding to a mean velocity of about 9×10^5 m s^{-1}.

Several novel quantum phenomena relating to the electrical properties of low-dimensional semiconductor heterostructures have been reported recently. These include the quantisation of the conductance of a one-dimensional channel [1, 2], electron focusing effects [3] and tunnelling into hybrid magneto-electric states of quantum wells [4–7]. All of these effects rely on the ballistic motion of conduction electrons over distances of the order of 0.1 μm. These investigations have been carried out with the devices operating at liquid-nitrogen temperatures or below. Hence quantum-size effects and ballistic transport are generally thought of as low-temperature phenomena.

In this Letter, we show that conduction electrons in appropriately designed resonant tunnelling devices can travel ballistically over distances of >0.1 μm even at room temperature, giving rise to clear quantum effects in the electrical conductance. Low-temperature measurements reveal up to 70 resonant peaks in the conductance and allow us to demonstrate experimentally a well known quantum effect, namely that maxima occur in the transmission coefficient of a barrier when the barrier width equals an integral or half-integral number of de Broglie wavelengths [8].

The double-barrier resonant tunnelling devices were grown by molecular beam epitaxy at a temperature of 630 °C on GaAs substrates heavily doped with Si (electron carrier concentration $n = 2 \times 10^{18}$ cm^{-3}). Device I consisted of the following layers, in order of growth from the substrate: (i) a 2 μm thick buffer layer of GaAs doped at $n = 2 \times 10^{18}$ cm^{-3}; (ii) 50 nm of GaAs, $n = 2 \times 10^{16}$ cm^{-3}; (iii) a 2.5 nm thick spacer layer of undoped GaAs; (iv) an undoped (AlGa)As barrier of thickness $b = 5.6$ nm, [Al] = 0.4; (v) an undoped GaAs well of width $w = 60$ nm; (vi) an undoped (AlGa)As barrier, $b = 5.6$ nm, [Al] = 0.4; (vii) a 2.5 nm thick spacer layer of undoped GaAs; (viii) 50 nm of GaAs, $n = 2 \times 10^{16}$ cm^{-3}; and (ix) a 0.5 μm top contact layer of GaAs, $n = 2 \times 10^{18}$ cm^{-3}. Device II was of similar composition apart from the well, layer (v), which was 120 nm wide. A third device of well width 180 nm was also examined. Mesas of

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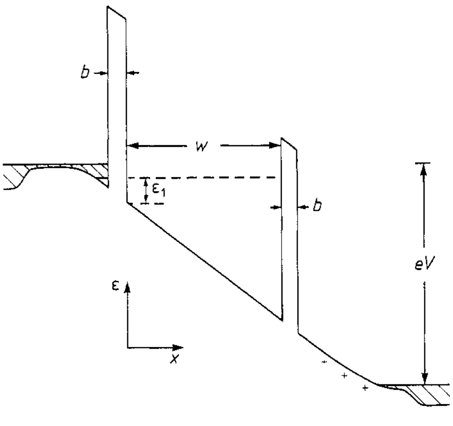

Figure 1. A schematic diagram of the variation of the electron potential energy in a double-barrier device under an applied voltage V.

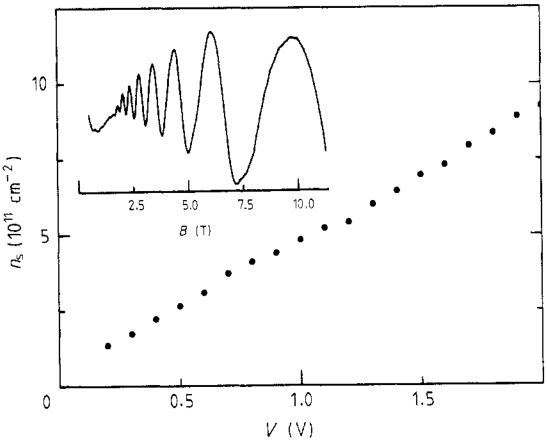

Figure 2. The variation with applied voltage V of the sheet density n_s of the two-dimensional electron gas in the accumulation layer of the emitter contact for device I (60 nm well). The values are deduced at each bias from the magneto-oscillations in the tunnel current using the relations $n_s = 2eB_f/h$ where $B_f^{-1} = \Delta(1/B)$ is the periodicity of the oscillations. The inset shows a typical set of magneto-oscillations (dI/dB) at a fixed bias of $V = 1.6$ V.

diameter 100 μm were etched and Ohmic contacts made to the substrate and top contact. The graded doping in the contacts and the undoped spacer layers adjacent to the barriers were designed to improve the performance of the devices by reducing dopant diffusion into the barriers. It is known that elastic scattering of tunnelling electrons by, for example, ionised impurities has an adverse effect on the electrical properties of resonant tunnelling devices [9].

A schematic diagram of the variation of the electron potential energy across the structure is shown in figure 1. An applied voltage leads to the formation of a quasi-two-dimensional electron gas (2DEG) in the accumulation layer adjacent to the emitter barrier (the barrier on the left in figure 1). The relatively low current densities mean that the electrons in the 2DEG have sufficient time to thermalise before tunnelling, since the mean time spent in the accumulation layer (~1 ns) is longer than the energy relaxation time due to acoustic phonon emission (~0.1 ns). Hence the 2DEG is degenerate at low temperatures. The sheet density n_s of the 2DEG can be determined from the period $\Delta(1/B)$ of the magneto-oscillations in the tunnel current which occur when a magnetic field is applied perpendicular to the barrier interfaces ($\boldsymbol{B} \| \boldsymbol{J}$): $n_s = 2eB_f/h$ where $B_f^{-1} = \Delta(1/B)$; see [10]. These magneto-oscillations are due to Landau levels passing through the quasi-Fermi level of the 2DEG as the magnetic field is increased. Figure 2

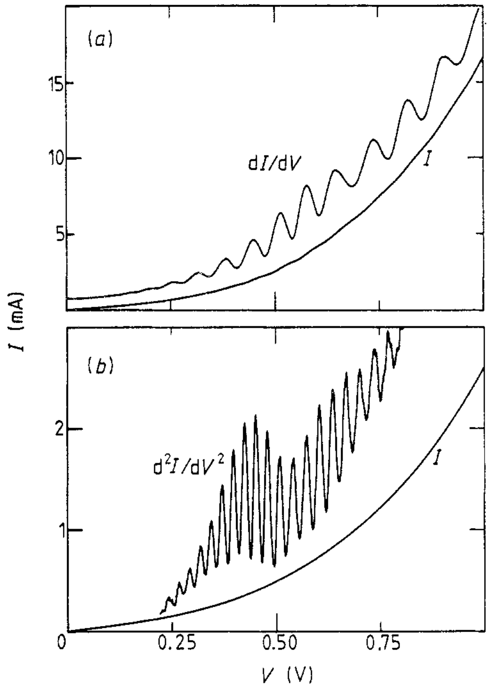

Figure 3. Room-temperature ($T = 300$ K) plots of the current–voltage characteristics $I(V)$ and derivatives. (*a*) Device I. (*b*) Device II.

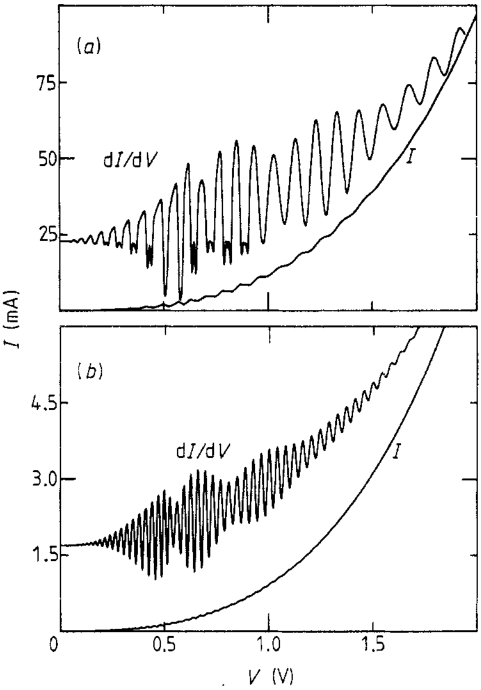

Figure 4. Plots at $T = 4$ K of the current–voltage characteristics $I(V)$ and the differential conductance dI/dV. (*a*) Device I. (*b*) Device II.

shows the variation of n_s with applied voltage for device I. The inset shows a typical series of magneto-oscillations obtained at a fixed bias $V = 1.6$ V.

The current–voltage characteristics, $I(V)$, of device I (60 nm well) at a temperature of 290 K are shown in figure 3(*a*) with the substrate biased positive. The differential conductance dI/dV is also plotted since it shows more clearly the oscillatory structure associated with resonant tunnelling. A total of 18 resonances can be seen. These room-temperature resonances in dI/dV are comparable in quality to those reported recently for a narrower quasi-parabolic well of width 31 nm [11]. None of the resonances show negative differential conductivity (NDC) at room temperature. For device II, the resonances are much weaker but are clearly seen in the second derivative, d^2I/dV^2 (see figure 3(*b*)). We can then identify 28 resonances at room temperature. For both structures, similar resonances are seen in the opposite bias direction (substrate negative), but with slightly reduced amplitudes. The origin of this difference is not clear, but may be associated with the difference in quality of the barrier interfaces.

When the devices are operated at a temperature of 4 K, the resonant structure in $I(V)$ is much more pronounced, as shown in figure 4. Device I shows 28 resonances, with 16 regions of NDC. The splitting of the minima in the conductance in the voltage range 200 to 900 mV in figure 4(*a*) is characteristic of the onset of high-frequency oscillations in the tunnel current in the region of NDC [12, 13]. At 4 K, device II (120 nm wide well) shows up to 70 peaks in conductance with 23 regions of NDC. The third device, with a well width of 180 nm, showed about 50 resonant peaks in conductance at 4 K, but no NDC.

Each of the peaks in conductance corresponds to a coincidence between the energy of a quasi-bound state of the quantum well with that of the 2DEG in the accumulation layer of the emitter contact. Note that for quantum wells of this width, the quasi-bound states of the well are strongly affected by the presence of the large electric field (see figure 1) and approximate to the eigenstates of a Stark ladder.

One of the interesting features of the data is that the resonances can be observed for applied voltages well above 1 V. At these voltages, electrons reach the collector barrier (on the right in figure 1) with a kinetic energy that exceeds the height of the potential barrier. At each applied voltage, we can determine the potential profile throughout the device from the value of n_s, which we measure, and from the distribution of negative space charge in the accumulation layer of the emitter contact. We can estimate the latter by using a Fang–Howard [14] wavefunction to describe the quasi-bound state of the 2DEG. Using this procedure, we estimate that for device I the resonances occurring at applied voltages above 590 mV (450 mV for device II) correspond to tunnelling into virtual states whose energy exceeds the height of the collector barrier potential. These 'over the barrier' resonances arise from the partial reflection of the de Broglie wave at the collector barrier.

The finite thickness of the collector barrier gives rise to another interesting quantum mechanical effect. For a rectangular barrier, it is well known that the reflection coefficient falls to zero when an integral or half-integral number of de Broglie wavelengths fit within its width [8]. In our device, the potential drop across the collector barrier means that the reflection coefficient is a minimum rather than zero when this condition is satisfied. For a varying potential the reflection coefficient is a minimum when

$$\int_0^b k(x)\,\mathrm{d}x = n\pi \tag{1}$$

where the integral is taken over the collector barrier, $n = 1, 2, 3, \ldots$, and $k(x)$, the electron wavenumber, is given by the kinetic energy and effective mass of the electron in the collector barrier region. Since the 'over the barrier' resonant states of the well arise from a standing-wave interference between the waves incident on and reflected from the collector barrier, we expect the amplitude of the oscillatory structure in the conductance to be a minimum when equation (1) is satisfied. The transmission probability of a double barrier incorporating a wide well has been modelled recently by Potter and Lakhani [15]. Although their analysis is for the case when there is no electric field in the well, it shows a beating effect which is qualitatively similar to that seen clearly in our data, both at 4 K and at room temperature (see figures 3 and 4).

The highest value V_m of applied voltage at which resonances can be observed in device I is 2.1 V. At this bias the electron sheet density in the accumulation layer of the emitter is $n_s = 9.5 \times 10^{11}\ \mathrm{cm}^{-2}$, corresponding to an electric field in the well of $E_w = 1.4 \times 10^7\ \mathrm{V\,m}^{-1}$. The corresponding voltage drop across the well is $V_w = 0.84$ V. For device II the corresponding values of V_m, n_s and V_w are 2.4 V, $7 \times 10^{11}\ \mathrm{cm}^{-2}$ and 1.2 V respectively. Thus resonances in $\mathrm{d}I/\mathrm{d}V$ are still observed even when electrons reach the collector barrier with kinetic energies of 1 eV or more. The existence of well defined resonances in $\mathrm{d}I/\mathrm{d}V$ implies a coherent standing-wave state in the well. In semi-classical terms, a *significant fraction* of the electrons that contribute to the measured current must have made at least two traversals of the well (forward and back) before undergoing a scattering process. At these energies electrons can emit a longitudinal optic (LO) phonon and scatter either into a lower-energy state of the Γ conduction band minimum or else into the L and X minima by emitting a zone boundary phonon. To our knowledge the associated LO phonon scattering rates have not been calculated for a hot electron moving in a quantum well in the presence of a large electric field ($E \simeq 10^7\ \mathrm{V\ m^{-1}}$). However, we can expect the typical electron lifetime to be ≃200 fs [16] for Γ–Γ scattering and ≃60 fs for Γ–L and Γ–X scattering [17].

If the electron is injected into the well with kinetic energy ε_1 (see figure 1), the classical traversal time from the emitter to the collector barrier τ_c is given by

$$\tau_c = \int_0^w \frac{dx}{v_g} = \frac{\hbar}{eE}(k(\varepsilon_1 + eEw) - k(\varepsilon_1))$$

where v_g is the group velocity. We can estimate τ_c at each bias from the values of ε_1 and E (obtained from the measured value of n_s) and from the non-parabolic dispersion relation for conduction electrons in GaAs [18]. This gives $2\tau_c = 140$ fs for two traversals of the well in device I at an applied bias of 870 mV. At this voltage the device exhibits clear NDC even though the electrons arrive at the collector barrier with a kinetic energy of 450 meV, which is well above the energy of the L minima and the potential height (for Γ minimum) of the barrier. This value of $2\tau_c$ is shorter than the expected mean time for Γ–Γ scattering but somewhat longer than that for Γ–L scattering. Note also that $2\tau_c$ is comparable to the period of vibration of the LO phonon mode and that the mean traversal velocity is $9 \times 10^5\ \mathrm{m\ s^{-1}}$, well above the saturation velocity for bulk GaAs.

An accurate estimate of the fraction $\Delta n/n$ of electrons that make two traversals of the well ballistically would require a detailed knowledge of the energy width of the quasi-bound resonant states in the well. The energy width is determined by monolayer fluctuations in the well thickness, scattering processes and the transmission rate through the collector barrier. In addition, it is known that charge build-up in the well leads to an electrostatic broadening of the resonant peaks in $I(V)$ (see [10]). However, a lower limit for $\Delta n/n$ can be estimated from the peak–valley ratio I_p/I_v since we expect that $\Delta n/n > (I_p - I_v)/I_p$. For the 60 nm well $I_p/I_v = 1.75$ at $V = 500$ mV and 4 K, giving $\Delta n/n > 0.4$. For the 120 nm wide well, the corresponding figure is $\Delta n/n > 0.2$ at 420 mV.

To summarise, we have described the electrical properties of double-barrier resonant tunnelling structures that incorporate well widths up to 180 nm. Even at room temperature a significant proportion of conduction electrons travel ballistically and give rise to clear quantum resonances in the differential conductance. We observe a beating in the amplitude of the resonances at high voltage due to an interference effect involving the collector barrier.

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