QUANTUM INTERFERENCE AND SPACE CHARGE EFFECTS IN DOUBLE BARRIER STRUCTURES INCORPORATING WIDE QUANTUM WELLS

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ABSTRACT

The current-voltage characteristics of resonant tunneling devices with well widths between 12 and 180 nm are studied. The voltage interval between the resonant peaks in the current is measured as a function of well width. For the wide wells the amplitude of the peaks in the differential conductance is modulated by an "over the barrier" interference effect involving the collector barrier. Space charge buildup and intrinsic bistability effects for a particular resonant state are found to depend critically on its energy difference from the top of the collector barrier and from lower lying standing wave states of the quantum well.

KEYWORDS

Resonant tunneling; double barrier devices; wide wells; intrinsic bistability; quantum interference.

It is now fifteen years since Chang, Esaki and Tsu (1974) reported the first observation of resonant tunneling in a double barrier heterostructure device. Devices of this type still attract considerable interest not only because of their potential for high frequency electronic applications (Sollner, 1983; Hiyamizu and co-workers, 1988) but also because they can reveal new physical effects such as intrinsic bistability (Alves and co-workers, 1988; Leadbeater and co-workers, 1988; Zaslavsky and co-workers, 1988) and a range of remarkable magnetotunneling properties (Alves and co-workers, 1989; Held and co-workers, 1989).

In this paper we investigate a series of double barrier resonant tunneling devices (RTD) based on n-type GaAs/(AlGa)As and grown by molecular beam epitaxy (MBE) with well thicknesses between 12 and 180 nm. The layers were grown at a temperature of 630 °C on silicon-doped GaAs (100)-substrates (n=2x10^{18} cm^{-3}). The aluminium mole fraction in the (AlGa)As barrier layers was x=0.4. Undoped GaAs spacer layers separate barrier and well regions from the doped contact layers. The spacer layers appear to improve the resonant tunneling characteristics. A possible explanation is that the ionised impurity scattering in the resonant tunneling region is thereby reduced. Structures A to E had barriers of thickness b=5.6 nm whereas for structure F, b=8.5 nm. The well widths for structures A,B,C,D,E and F were 12, 22, 60, 120, 180 and 120 nm respectively. The composition of the devices is given below.

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Thickness</th>
<th>Composition</th>
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<tbody>
<tr>
<td>0.5 μm thick n⁺GaAs top contact layer</td>
<td>(2x10^{18} cm⁻³)</td>
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<tr>
<td>50 nm thick n-GaAs</td>
<td>(2x10^{16} cm⁻³)</td>
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<tr>
<td>2.5 nm thick GaAs spacer layer (undoped)</td>
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<tr>
<td>(AlGa)As barrier of thickness b, [Al]=0.4 (undoped)</td>
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<tr>
<td>GaAs well of thickness w (undoped)</td>
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<tr>
<td>(AlGa)As barrier of thickness b, [Al]=0.4 (undoped)</td>
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<tr>
<td>50 nm thick n-GaAs</td>
<td>(2x10^{16} cm⁻³)</td>
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<tr>
<td>2 μm thick n⁺GaAs buffer layer (2x10^{18} cm⁻³)</td>
<td></td>
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<tr>
<td>n⁺ GaAs substrate</td>
<td>(2x10^{18} cm⁻³)</td>
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The devices were processed using optical lithography and chemical etching to form mesa of diameter 100 and 200 μm.

A schematic diagram of the variation of the electron potential energy across the structure is shown in the inset in Fig. 1. Because of the light doping in the regions close to the barriers, an applied voltage produces accumulation and depletion regions shown in yellow and pink, respectively. The quasi-two dimensional electron gas (2DEG) which forms in the accumulation layer. The low current density passed by the devices means that the average lifetime of an electron in the accumulation layer is relatively long (≈1 ns), so that electrons arriving from the heavily doped regions have time to thermalize before tunneling. Resonant tunneling occurs when the quasi-bound state energy of the 2DEG matches that of a standing wave state of the well. The well states are strongly affected by the large electric field and approximate to the eigenstates of a Stark ladder (see inset Fig. 1). The current-voltage characteristics I(V) and derivatives (dI/dV or d²I/dV²) at 4 K are shown in Fig. 1 for all devices (boxes A to F). The substrate is biased positive. Devices A, B, C and D all show negative differential conductivity (NDC). As the width of the well increases the number of resonances observed increases (up to 70 for device D) and their amplitude decreases. For structures E and F resonances are clearly seen only in the second derivative d²I/dV². The existence of well-defined resonances implies coherent standing-wave states in the well. Therefore a single electron must first make a transition from the lower quasi-bound state to the higher adjacent state. If the energy of the well without scattering even when they have kinetic energies of several hundred meV. The widest well in which we have observed resonances is device E (180 nm) in which case some electrons would have to travel 360 nm ballistically. A device with a 240 nm wide well was grown, but showed no quantum interference effects. For structures A to D resonances were sharply identifiable at room temperature. Note that for devices C to F most resonances occur at voltages for which electrons reach the collector barrier with kinetic energies exceeding the height of the potential step. These "over the barrier" resonances arise from the partial reflection of de Broglie waves at the potential discontinuity.

Fig. 1B for the 22 nm wide well structure is particularly noteworthy. Seven well-defined resonant peaks are observed in I(V). This series of peaks is interesting because it reveals three distinct types of behaviour as the current swings from its peak to valley value. NDC in a circuit can lead to high frequency oscillations in the current. This causes a characteristic "double step" in the DC I(V) characteristic in the NDC region (Sollner, 1987). The first resonance has peak/valley current ratio of 3.2/1. However, at low bias the magnitude of the NDC is so small that the current remains stable (i.e. no high frequency oscillations) when the voltage is held in the region of NDC. The I(V) curve in this region is therefore smooth. In the region of NDC beyond the second resonance, the current breaks into high frequency oscillations, as can be seen from the form of the derivative in the I(V) curve. For the third, fourth and fifth resonances, the increase in current from threshold to peak extends over a wide voltage range. This is clear evidence for the buildup of negative space charge in the quantum well during the resonant tunneling process (see Leadbeater and co-workers, 1988). For each of these resonances an electron tunneling into the well can undergo multiple reflections at the barriers and escape from the well by the emission of LO phonons. This process is fast (<1 ps) and leads to a significant buildup of charge in the well because electrons in the lower energy subbands tunnel out through the collector barrier relatively slowly. The buildup of space charge in the well in the fourth and fifth resonances is sufficiently strong to give rise to the now well-known intrinsic bistability effect over the voltage ranges 0.46 to 0.5 V and 0.68 to 0.73 V respectively (Alves and co-workers, 1988; Leadbeater and co-workers, 1988; Zaslavsky and co-workers, 1988). The absence of strong space charge buildup and intrinsic bistability at the second resonance in this device is probably due to the fact that the energy difference between the first and second subband is less than the energy of the LO phonon. Rapid thermalization by LO phonon emission is therefore improbable. Note that the voltage between current threshold and peak for the sixth and seventh resonances is considerably smaller than that for the fifth resonance. In addition, no intrinsic bistability is observed but instead the current breaks into high frequency oscillation when the device is biased in the region of NDC. The charge buildup in the well is much less for the sixth and seventh resonances because the energies of the corresponding quantum well states are above the top of the collector barrier. The life-times of the associated standing wave states are therefore very short and electrons tunnel out through the collector barrier before they have time to emit an LO phonon and scatter into one of the lower quasi-bound states of the well.

The finite thickness of the collector barrier gives rise to an interesting quantum mechanical effect which produces the beating pattern in the amplitude of the resonances for structures C, D, E and F at high biases (see the dI/dV and d²I/dV² plots in Fig. 1). 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 (Schiff, 1949). In our devices, 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 minimum when

$$\int_0^b k(x) \, dx = n\pi,$$

(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 device incorporating a wide well has been modelled recently by Potter and Lakhani (1988) although their analysis is for the case when there is no electric field in the well. We have calculated the transmission coefficient \( T^*T \) versus voltage for a RTD with \( b=6.5 \) nm and \( w=120 \) nm as is shown in Fig. 2. Our calculation uses the transfer matrix method (Brennan and Summers, 1987) within an Airy function approach, assuming that the applied voltage is dropped entirely across the barriers and well. The inset in Fig. 2 shows the calculated probability densities for an electron wave of energy 10 meV incident on the RTD for four different voltages (indicated by arrows in the figure). Note that when the voltage is at or near a resonant peak in \( T^*T \) the electron probability density \( \psi^*\psi \) in the well is large whereas it is small in the collector barrier (e.g. a and c in Fig. 2). In contrast, when the voltage is near a beat position the amplitude of the standing wave resonance in the well is small whereas it is large in the collector barrier. The effect of increasing the width of the collector barrier can be seen by comparing Figures 1D and 1F for two devices in which the well widths are the same (120 nm) but the barrier thicknesses differ. For the 5.6 nm barrier (Fig. 1D) 3 beats can be resolved whereas in Fig. 1F (8.5 nm barrier) 6 beats are clearly seen. This width dependence confirms the mechanism proposed above.

![Fig. 2. Transmission coefficient versus voltage for an electron wave incident on a double barrier structure with an energy of 10 meV. The calculation is for a 8.5 nm-120 nm-8.5 nm structure with 320 meV potential barrier and GaAs and (AlGa)As effective masses of 0.067me and 0.1me respectively. The inset shows the probability densities \( \psi^*\psi \) for four different voltages (indicated by arrows). The left-hand side of the emitter barrier is at \( x=0 \).](image)

In Fig. 3 we have assigned an integer \( N \) to each resonant peak in the current. The figure plots \( N \) against peak voltage \( V \) for devices A to E. As the well width increases the spacing between the peaks decreases. This reflects the decrease in the energy spacing of the quasi-bound states of the well. At high biases the \( N(V) \) curves become approximately linear. A detailed analysis of these curves is complicated since it is necessary to model the non-parabolicity of the GaAs conduction band at electron energies up to and above 1 eV. It is interesting to note that for device D (\( w=120 \) nm) the mean peak separation is \( \Delta V=39 \) mV over the range from 0.5 to 1.5 V. The corresponding energy \( \Delta E \) is approximately equal to the energy of the longitudinal optical phonon in GaAs (36 meV). Recently Bockenhoff and co-workers (1988) observed oscillations with similar values of \( \Delta V \) for a tunneling structure where the quantum well width was 100 nm. The collector barrier in that device was formed by a delta-doping spike of silicon donors. They suggested that the oscillatory structure which they observed was related to the "Hickmott" oscillations that occur in the \( I(V) \) characteristics of single barrier heterostructures of the type \( n\text{-GaAs/AlGaAs/}n'\text{GaAs} \) (Hickmott and co-workers, 1984). It is now fairly well-established that the Hickmott oscillations arise from a subtle process involving space charge effects and LO phonon energy relaxation of hot tunneling electrons (Eaves and co-workers, 1987 and references therein).
Quantum interference and space charge effects

Bockenhoff and co-workers suggested that in their devices the LO phonon emission process could be resonantly enhanced by the standing wave states of the quantum well. However, the magnetic field dependence of the resonances for B applied parallel to the plane of the barriers appears to be consistent with the evolution of standing wave states into hybrid magneto-electric states (Alves and co-workers, 1989). Our own measurements on structure D do not reveal any strong evidence of resonant coupling between the standing wave states of the well and the LO phonon mode. Although LO phonons can give rise to important effects in resonant tunneling devices (Leadbeater and co-workers, 1989), we attribute the resonances reported here to purely electronic standing wave states of the quantum well. Note that the mean peak separation for structure E is 25 meV which is less than the LO phonon energy.

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REFERENCES