Resonant magnetotunneling through individual self-assembled InAs quantum dots

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Resonant peaks are observed in the low-temperature current-voltage \( I(V) \) characteristics of a single-barrier GaAs/AlAs/GaAs diode with InAs quantum dots incorporated in the AlAs tunnel barrier. We argue that each peak arises from single-electron tunneling through a discrete zero-dimensional state of an individual InAs dot in the barrier. Each peak splits into sharp components for magnetic field \( B \) magnitude; the \( I(V) \) curve probes the density of Landau-quantized states in the emitter-accumulation layer. A dot size of \( \approx 10 \text{ nm} \) was estimated from the diamagnetic peak shift for \( B \perp I \).

An array of quantum dots (QD's) produced by self-organized (Stranski-Krastanov) heteroepitaxial growth is formed when more than a critical layer thickness is grown on certain surfaces of different chemical composition and lattice constant. The system that has received the most attention to date consists of InAs dots grown on a GaAs or (AlGa)As surface.\(^1\)\(^-\)\(^12\) The electronic states of self-assembled dots capped by lattice matched layers have been investigated mainly by optical spectroscopy\(^2\)\(^\text{,}3\)\(^\text{,}5\)\(^\text{,}7\)\(^\text{,}10\)\(^\text{,}12\) and capacitance spectroscopy\(^5\)\(^\text{,}6\). Due to variations in size, shape, and strain, a dot ensemble has a wide distribution of eigenenergies. Typically the optical spectra correspond to the dot ensemble\(^5\)\(^\text{,}10\)\(^\text{,}12\), however, photoluminescence and cathodoluminescence spectra taken on submicron areas reveal emission lines corresponding to individual dots.\(^2\)\(^\text{,}3\)\(^\text{,}7\)

In this paper we report tunnel current investigations of the ensemble \( I(V) \) characteristics of a single-barrier GaAs/AlAs/GaAs heterostructure. By tuning the applied voltage we can observe resonant tunneling through an individual dot. We use magnetotunneling spectroscopy to probe the initial and final states in the tunneling transition. We are also able to estimate the spatial extent of the confined electron wave function in the dot. In addition, the tunnel current through the localized state is also a sensitive probe of the properties of the electrons in the emitter contact.

Our device was prepared by first growing a 1-\( \mu \text{m} \)-thick GaAs buffer layer with graded Si doping on a \( (100) \) \( n^+ \)-GaAs substrate, followed by 100 nm of undoped GaAs and 5 nm of AlAs. The QD's were formed by growing 1.8 ML of InAs on the AlAs at a growth temperature of 520 °C. The dots were then nominally capped with a further 5 nm of AlAs, thus creating a 10-nm AlAs tunnel barrier. This was followed by an undoped 100-nm GaAs layer and capped by 1 \( \mu \text{m} \) of \( n^+ \)-GaAs of graded doping. Since we cannot exclude possible Al alloying, the dots should strictly be referred to as \( n^+ \)-GaAs layers. 1.8 monolayers of InAs was alloyed into the \( n^+ \)-GaAs layers to form Ohmic contacts.

To characterize the device, scanning electron and tunneling microscopy (SEM and STM) and photoluminescence (PL) spectroscopy were used. SEM and STM imaging was performed on samples of the same design but with the growth terminated after depositing the InAs layers. It allowed us to estimate the density of dots as \( \approx 2 \times 10^{11} \text{ cm}^{-2} \), with a dot size \( \approx (10 \times 10) \text{ nm}^2 \). A PL spectrum of our tunnel structure, recorded with a Ge detector using He-Ne laser excitation (\( \lambda = 6328 \text{ Å} \)), is shown in the inset of Fig. 1. The spectrum exhibits a broad line with a maximum a few hundred meV below the GaAs band-gap energy. The line corresponds to the emission from the dot ensemble and is similar to that reported by other groups.\(^2\)\(^\text{,}11\)\(^\text{,}12\)

The expected conduction-band potential profile for our device is shown in Fig. 1. When a voltage \( V \) is applied between collector and emitter, a two-dimensional electron gas (2DEG), degenerate at low temperatures, accumulates in the undoped GaAs region adjacent to the tunnel barrier. Resonant tunnelling occurs if an electronic state of a QD in the barrier is resonant with a state in the 2DEG. Note that \( V \) is the external voltage applied to the device while the voltage drop \( V_1 \) between the 2DEG Fermi level and the states in the middle of the barrier is only a small fraction of \( V \). As \( V_1 \) depends nonlinearly on \( V \) because of charge redistribution in the structure, we define the leverage factor \( f \) as \((dV_1/dV)^{-1}\).

The current-voltage characteristics \( I(V) \), recorded for a
100-μm-diameter mesa in the absence of magnetic field, are shown in Fig. 2. *Forward* and *reverse* bias correspond to electron flow from and to the substrate, respectively. An I(V) curve for the control sample is also shown for comparison. Both devices have a very high impedance (~10^{13} Ω) around zero bias and exhibit a monotonically increasing background current. In addition, pronounced, low-current (a few pA) peaks, superimposed on the background current, are observed for the InAs quantum dot device for *forward* bias above 100 mV at 4.2 K. The peaks are absent in *reverse* bias at 4.2 K, where there is only indistinct structure. On lowering the temperature to 0.4 K, the structure in *reverse* bias evolves into a set of distinct steps. The I(V) curve of the control sample has no structure in either bias direction but the background current is of similar magnitude.

The peaks in I(V) arise from resonant tunneling through states in the barrier, and our observations indicate that these states are associated with the incorporation of InAs in the barrier. We argue that resonant tunneling occurs through discrete (zero-dimensional) electron states of individual InAs quantum dots in the barrier. To confirm this, we now examine the effect of magnetic field B on the tunneling current in *forward* bias. For B applied parallel to the current, the I(V) curves change qualitatively as shown in Fig. 2. At fields as low as 0.4 T a series of narrow peaks arises in the curves. The peaks diverge in bias and their number falls with increasing B up to 3–4 T. Increasing B from 4 to 12 T causes the peaks to shift to lower bias with little change in shape.

Figure 3(a) shows examples of I(B) at constant bias V_0. If V_0 is equal or close to the bias at which a peak occurs at 0 T, there are pronounced oscillations in I(B). Their maxima and minima shift to smaller B with increasing V_0. The I(B) curves exhibit no structure at V_0 just below or above a peak in I(V).

We attribute the sharp peaks in I(V) to the Landau quantization of the 2DEG in the emitter which is consistent both with the peak divergence with increasing B and with their shift to lower V. As to the oscillations in I(B), these behave quite differently from magneto-oscillations reported earlier in single-barrier tunneling devices, for which the maxima should shift to higher B with increasing V_0. In our case a maximum in I(B) occurs when the magnetic field brings an occupied Landau level in the 2DEG into resonance with an energy level in the barrier. In effect, both I(V) and I(B) probe the local density of states (DOS) of the 2DEG in the emitter accumulation layer.

This is illustrated in Fig. 3(b) by a fan chart of I(V)-peak positions in the range of low B. Despite the complexity of the picture due to many overlapping lines, a distinct pattern emerges: the peaks shift to lower voltage, and with their shift to lower V. As to the oscillations in I(B), these behave quite differently from magneto-oscillations reported earlier in single-barrier tunneling devices, for which the maxima should shift to higher B with increasing V_0. In our case a maximum in I(B) occurs when the magnetic field brings an occupied Landau level in the 2DEG into resonance with an energy level in the barrier. In effect, both I(V) and I(B) probe the local density of states (DOS) of the 2DEG in the emitter accumulation layer.
Such resolution is possible only if, for each Landau-level electrons where the cyclotron splitting is less than 1 meV. The peak positions shift to lower voltage quadratically for the lower-voltage characteristics shown in Fig. 4 between forward and reverse bias. The asymmetry of dot positions in the AlAs barrier. The dots are grown on the center plane of the barrier, but the covering AlAs layer is effectively thinner due to the size and shape of the dots. Thus for reverse bias the tunneling rate into a dot which may at high enough bias be dominated by inelastic processes is much greater than the rate of tunneling out. As each dot level moves below the emitter Fermi level, it gives rise to a distinct step in the I(V) curve since it opens a new tunneling channel. Conversely, for forward bias the tunneling rate out of the dots is higher than the tunneling-in rate, and the current is a voltage-tunable probe of single-particle energy levels in the emitter.

The conclusion that each peak in I(V) corresponds to tunneling through an individual dot is also supported by the peak current values. In this asymmetric geometry the tunnel current through a single dot can be written as \( I = e v \exp(-2kd) \), where \( v \) is the attempt frequency, \( d = 5 \) nm is the barrier half-thickness, \( h \kappa = \sqrt{2m^* \Delta E} \), and \( \Delta E \) is the height of the barrier. Using the effective mass \( m^* = 0.067m_e \) and \( \Delta E = 0.8 \) eV, expected for this heterostructure system, we obtain peak current values of a few pA, consistent with the experiment.

The question remains open as to why we observe tunneling through a single dot rather than the ensemble of about 10^7 dots in a typical mesa. The PL spectrum from the sample (Fig. 1) indicates that for the majority of dots the electron ground energy level is below the conduction-band edge \( E_c \), in agreement with capacitance spectroscopy studies. These levels are unavailable for energy-conserving tunneling processes. Resonant tunneling processes probe only extremal dots with electron level energies above \( E_c \). Such dots can arise due to fluctuations in size (30–40%), shape, strain, and AlAs coverage or possible Al alloying of dots. Our pic-
tire implies that a fraction of dots should be charged at zero bias, in order to align the chemical potentials of the dot ensemble and the collector and emitter $n$-doped contact layers. Under bias, the accumulation of the 2DEG is followed by the dot discharge, which contributes strongly to the leverage factor dependence on voltage.

In conclusion, we have observed resonant tunneling through single, independent electron states which are associated with self-assembled InAs quantum dots embedded in an AlAs matrix. The variation of the tunnel current with $B$ provides information about the spatial extent of the dot wave function. In addition, the localized character of the electronic states means that the tunneling is also potentially a very sensitive way of probing the density of states in the emitter 2DEG, which has not been possible in previous experiments.

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