Superlattices and Microstructures, Vol. 21, No. 2, 1997

Resonant magnetotunneling through individual self-assembled InAs quantum dots

A. Thornton, I. E. Itskevich†, T. Ihn, M. Henini, P. Moriarty, A. Nogaret, P. H. Beton, L. Eaves, P. C. Main, J. R. Middleton, M. Heath

Department of Physics, University of Nottingham, University Park, Nottingham, NG7 2RD, U.K.

(Received 15 July 1996)

A single-barrier GaAs/AlAs/GaAs heterostructure, with self-assembled In-based quantum dots incorporated in the AlAs tunnel barrier, exhibits a series of resonant peaks in the low temperature current–voltage characteristics. We argue that each peak arises from *single-electron* tunneling through the *discrete zero-dimensional* state of an *individual* InAs dot. We use the tunneling for fine probing of the local density of states in the emitter-accumulation layer. Landau-quantized states are resolved at magnetic field $B \parallel I$ as low as 0.2 T. Spin-splitting of the dot electron states has been observed for $B \perp I$.

The electronic states of self-assembled quantum dots (QDs) produced by self-organized (Stranski–Krastanov) heteroepitaxial growth have been so far investigated by optical [1] and capacitance [2] spectroscopy. We have developed a new approach for studying the self-assembled QDs, embedding them in the barrier layer of a single-barrier tunneling heterostructure device. Here we report tunneling-current investigations of self-assembled InAs QDs.

Our device was grown on a (100) n^+-GaAs substrate and comprises the following layers: 1 μm of GaAs with graded Si doping; 100 nm of undoped GaAs; 5 nm of AlAs; 1.8 monolayers of InAs which form the QDs; 5 nm of AlAs; 100 nm of undoped GaAs; 1 μm of GaAs of graded doping. Thus the total width of the AlAs barrier is 10 nm. Circular mesas of various diameters, from 30 to 400 μm, were produced using optical lithography. AuGe was alloyed into the n^+-GaAs layer to form an ohmic top-contact. The density of dots of $\approx 2 \times 10^{11}$ cm^{-2} and a typical dot size of $\approx (10 \times 10)$ nm^2 were estimated by scanning electron and tunneling microscopy performed on samples of the same design but with the growth terminated after deposition of the InAs layer. A photoluminescence (PL) spectrum of our structure (see Fig. 1A) exhibits a broad line with a maximum a few hundred meV below the GaAs band-gap energy, similar to observations of other groups [1]. The line corresponds to the emission from the dot *ensemble*.

When a voltage V is applied between the contacts, a two-dimensional electron gas (2DEG) accumulates in

† On leave from Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, Moscow district, 142432, Russia.

0749–6036/97/020255 + 04 $25.00/0 sm960192

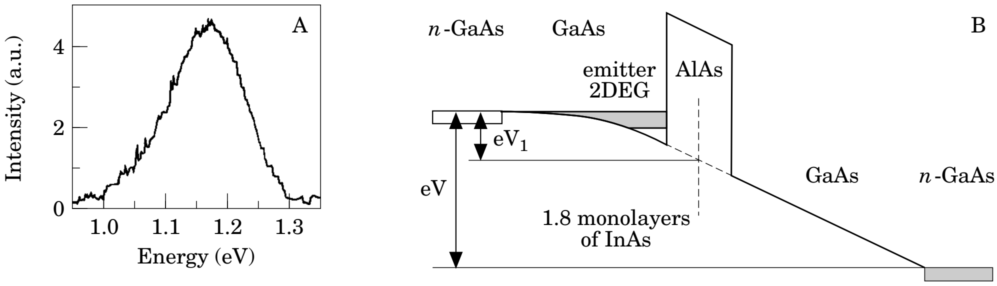

Fig. 1. (A) Photoluminescence spectrum from the sample at He-Ne laser excitation. (B) A schematic conduction band diagram of the sample under an applied voltage V.

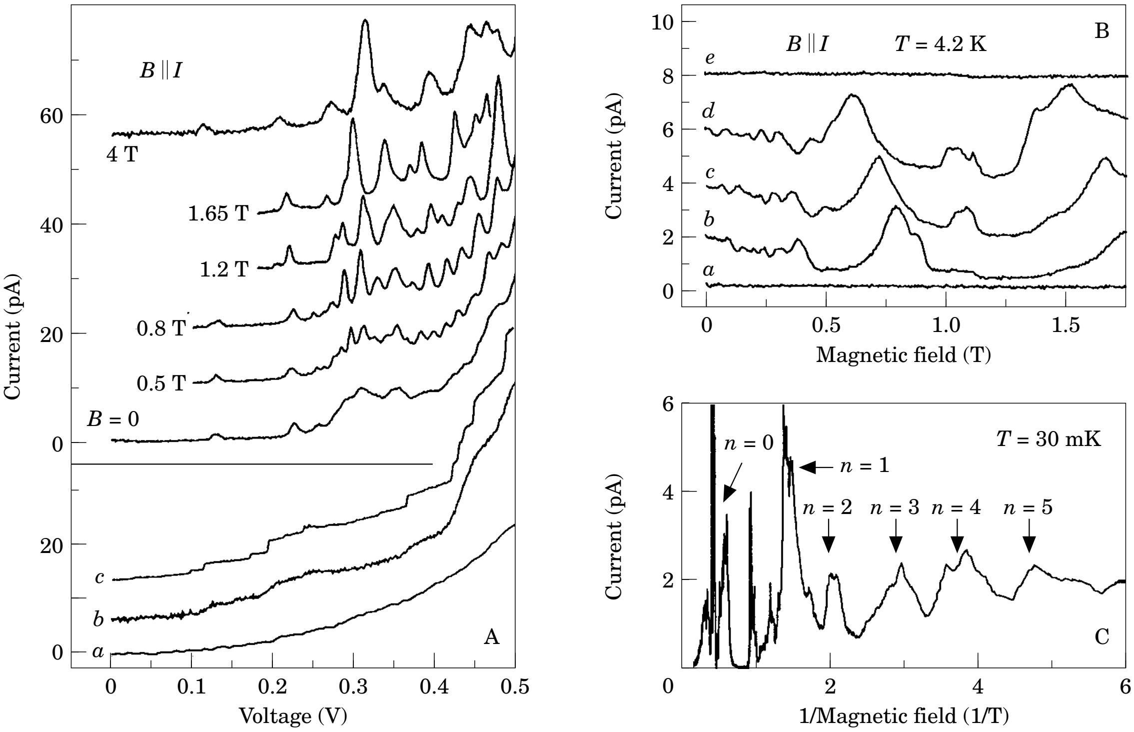

Fig. 2. (A) The $I(V)$ characteristics of a 100 μm diameter mesa. Lower: (A) control sample; (B) for $B = 0$ in *reverse* bias at 4.2 K and (C) at 0.35 K. Upper: $I(V)$ in *forward* bias at 4.2 K at various $B \parallel I$. Curves are offset. (B) $I(B)$ characteristics at various V: *a*, 105 mV; *b*, 114 mV; *c*, 115 mV; *d*, 116 mV; *e*, 130 mV. Curves are offset. (C) $I(B)$ curve at $V = 115$ mV plotted versus $1/B$. Numbers of resonant Landau levels (*not* filling factors) are indicated.

the undoped GaAs layer near the tunnel barrier (see Fig. 1B). Resonant tunneling occurs when an electronic state in the barrier is resonant with a state in the 2DEG. Note that the voltage drop V_1 between the 2DEG and the middle of the barrier is only a small fraction ($\sim$ 10%) of the applied bias V and that the leverage factor $f = (\partial V_1/\partial V)^{-1}$ can depend strongly on V.

The lower part of Fig. 2A shows the current–voltage $I(V)$ characteristics for a 100 μm diameter mesa at zero magnetic field. *Forward* bias corresponds to electron flow *from* the substrate. $I(V)$ for a control sample of similar design but lacking the InAs layer is shown for comparison. Both devices have very high impedance

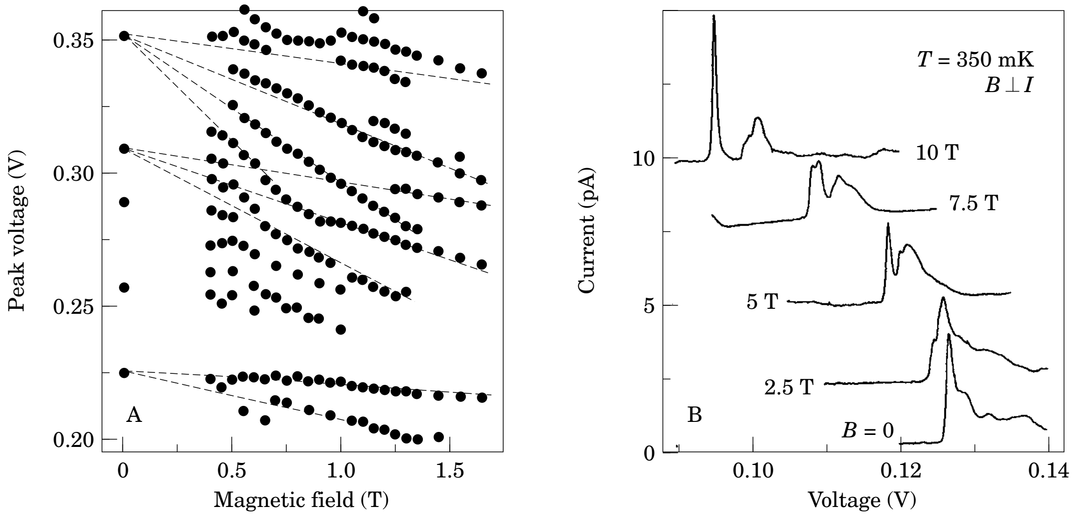

Fig. 3. (A) Fan chart of the peaks in $I(V)$ versus $B \parallel I$. (B) $I(V)$ characteristics at various $B \perp I$. Curves are offset.

($\sim 10^{12}$ Ω) around zero bias and monotonically increasing background currents of similar magnitude. In addition, pronounced low-current (a few pA) peaks are observed for the InAs quantum dot device for *forward* bias above 100 mV.

We argue that each of the peaks is due to *single-electron* resonant tunneling through an *individual* QD in the barrier. The peak currents of a few pA are consistent with *single-electron* tunneling for the parameters of our heterostructure (i.e. barrier height and width and effective mass). Further evidence is in the $I(V)$ curves in *reverse* bias, which show only indistinct structure at 4.2 K, but on lowering the temperature to 0.4 K evolve into a set of sharp steps. These are fingerprints of quantized charge build-up in 0D states in the barrier which might belong to the QDs [3]. The charge build-up arises due to the asymmetry of dot positions in the AlAs barrier, because the AlAs layer covering the dots is effectively thinner than that on the substrate side due to the finite dot size.

The most striking evidence for *single-electron* tunneling through *individual* 0D states comes from measurements in magnetic field B applied parallel to the current (see upper part of Fig. 2A). In B as low as 0.4 T a series of narrow peaks arises in the $I(V)$ curves in *forward* bias. 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.

The peaks in $I(V)$ reflect the Landau quantization of the 2DEG in the emitter. This is confirmed by studying $I(B)$ taken at constant bias V_0 (see Fig. 2B). The $I(B)$ curves exhibit no structure at V_0 just below or above a peak in $I(V)$, but there are pronounced oscillations in $I(B)$ if V_0 is equal or close to the bias at which a peak occurs. The maxima and minima of the oscillations shift to *smaller* B with increasing V_0. Figure 2C shows that maxima in $I(B)$ are periodic in $1/B$. The maxima occur when the magnetic field brings an occupied Landau level (LL) in the 2DEG in resonance with the QD level in the barrier. We can resolve the maximum due to the LL with $n = 5$ at B as low as 0.2 T, with the 2DEG concentration $\approx 6 \times 10^{10}$ cm^{-2}. In effect, both $I(V)$ and $I(B)$ probe the local 2DEG density of states (DOS), though contributions from interaction effects and chemical potential oscillations should be taken into account for an interpretation of the data.

The DOS probing is illustrated in Fig. 3A 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 there are a few sets of peaks diverging with B. The dashed lines are guides for the eye corresponding to possible LL-fans, each originating from a single QD.

Applying $B \perp I$ causes the diamagnetic shift of peaks to lower voltage. Fig. 3B shows the lowest-voltage peak splitting into two components with increasing B. We interpret this as a breaking of the spin-degeneracy of the InAs QD. Using the leverage factor $f = 6.5$, as estimated from the LL splitting at $B \parallel I$, we find the QD electron g-factor as $|g^*| = 1.2 \pm 0.3$, much smaller than the value for bulk InAs. Different voltage widths of the spin-split components at $B = 10$ T may be evidence for partial spin polarization of the 2DEG, with the QD acting as a spin filter. The difference in voltage width $\approx g\mu_B B$ gives for 2DEG electrons $g \approx -0.5$, with the sign opposite to that for QDs.

From the diamagnetic shift of the peaks we estimate the size of the resonant states in the barrier as $\approx (10 \pm 5)$ nm. This rough estimate allows us to exclude 0D defect states in the barrier as a possible origin of resonant levels. To be resonant with the 2DEG in the emitter, defect states should be very deep in the AlAs band-gap and therefore localised on the scale of the lattice constant, inconsistent with the estimate above. Tunneling through 0D states of residual donors is also rejected, as no features are observed in $I(V)$ from the control sample. Therefore the resonant states in the barrier through which we observe the tunneling must be those of the InAs quantum dots.

An important question is: why do we observe tunneling through only a few single dots rather than the *ensemble* of about 10^7 dots in a typical mesa? The PL spectrum (Fig. 1) suggests that the ground electron energy level is *below* the conduction band edge E_c for the majority of QDs. These dots are unavailable for energy-conserving tunneling processes. We observe tunneling through extremal dots with electron level energies *above* E_c. Such dots can arise due to fluctuations in size, shape and strain or possible Al alloying of dots.

In conclusion, we have observed resonant tunneling through the electron states of *individual* self-assembled InAs quantum dots incorporated in an AlAs matrix. This appears a sensitive tool for fine probing the density of states of the 2DEG in the emitter-accumulation layer. At high $B \perp I$ a QD acts as a spin filter for the partially spin-polarized 2DEG.

Acknowledgements—We are grateful to M. Steer and M. S. Skolnick for help with the PL measurements. This work is supported by EPSRC (UK). I. E. I. and L. E. acknowledge the Royal Society and EPSRC for research fellowships.

References

[1] J.-Y. Marzin, J.-M. Gerard, A. Izraël, D. Barrier and G. Bastard, Phys. Rev. Lett. **73**, 716 (1994); S. Fafard, R. Leon, D. Leonard, J. L. Merz and P. M. Petroff, Phys. Rev. **B 50**, 8086 (1994); M. Grundmann, J. Christen, N. N. Ledentsov, J. Böhrer, D. Bimberg, S. S. Ruvimov, P. Werner, U. Richter, U. Gösele, J. Heydenreich, V. M. Ustinov, A. Yu. Egorov, A. E. Zhukov, P. S. Kop'ev and Zh. I. Alferov, Phys. Rev. Lett. **74**, 4043 (1995); D. I. Lubyshev, P. P. González-Borrero, E. Marega, Jr., E. Petitprez, N. La Scala, Jr. and P. Basmaji, Appl. Phys. Lett. **68**, 205 (1996); R. Heitz, M. Grundmann, N. N. Ledentsov, L. Eckey, M. Viet, D. Bimberg, V. M. Ustinov, A. Yu. Egorov, A. Zhukov, P. S. Kop'ev and Zh. I. Alferov, Appl. Phys. Lett. **68**, 361 (1996); M. Grundmann, N. N. Ledentsov, O. Stier, D. Bimberg, V. M. Ustinov, P. S. Kop'ev and Zh. I. Alferov, Appl. Phys. Lett. **68**, 979 (1996).

[2] H. Drexler, D. Leonard, W. Hansen, J. P. Kotthaus and P. M. Petroff, Phys. Rev. Lett. **73**, 2252 (1994); G. Medeiros-Ribeiro, D. Leonard and P. M. Petroff, Appl. Phys. Lett. **66**, 1767 (1995).

[3] B. Su, V. J. Goldman and J. E. Cunningham, Surface Sci. **305**, 566 (1994).