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Magneto-tunnelling spectroscopy of single self-assembled InAs quantum dots in AlAs

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Abstract

We observe the spin splitting of a single InAs quantum dot using magneto-tunnelling spectroscopy. The current–voltage characteristics at low temperature are dominated by a Fermi edge singularity, caused by electron interaction effects. We obtain a value for the g-factor ($=0.82 \pm 0.09$) for the quantum dot, with magnetic field applied in the plane of the dot. The magnetic field dependence of the amplitude of the tunnel current provides us with an estimate of the size of the quantum dot wave function (9 nm). © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Magneto-tunnelling; InAs; Quantum dots; Spin splitting

The spin splitting of the ground states of self-assembled InAs quantum dots (QDs) is expected to be small (<1 meV at 10 T), and its direct observation in optical spectroscopy is hampered by a broad line width due to the distribution of dot sizes. Sharp photoluminescence (PL) lines due to single InAs dots have been observed [1,2], but to our knowledge there have been no reports of the observation of spin splitting to date. The g-factor of the dots at high magnetic field can be obtained from capacitance spectroscopy, but there is some uncertainty in such results [3].

In this paper we use magneto-tunnelling spectroscopy to observe directly the spin splitting of a single InAs QD, and measure the g-factor of the electron ground state of the dot. Our method is similar to that used to observe spin-splitting of zero-dimensional impurity states within a quantum well [4].

Our device is an MBE-grown GaAs-based single barrier n–i–n tunnelling device, where InAs QDs have been grown in the centre of a 10 nm AlAs barrier. A more detailed description of the device is given in Ref. [5]. Fig. 1 shows the conduction band profile of the device under bias. The average diameter of the dots is about 10 nm, and the average height is 3 nm. The dots are grown on a 5 nm layer of AlAs, with a further 5 nm of AlAs grown above the dot layer. The amount of AlAs directly above the dots is expected to be less than 5 nm, however, introducing an asymmetry into our device. In our measurements we define forward bias such that electrons enter the device through the substrate and

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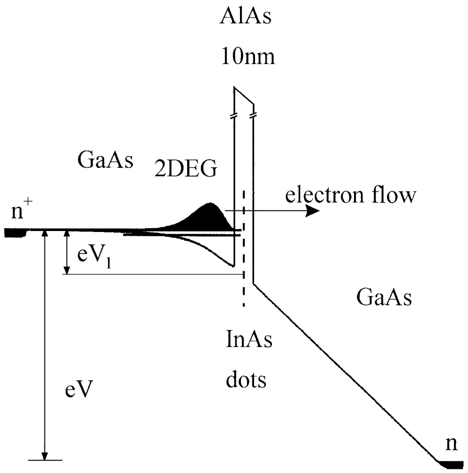

Fig. 1. Conduction band potential profile of the device under bias.

tunnel into the dots through the thicker 5 nm AlAs barrier, and out through the thinner barrier. Under a bias a 2DEG forms in front of the barrier, and at temperatures of around 4 K in forward bias we see isolated peaks, a few pA in height, on a background current of less than 0.25 pA. Each strong peak is due to electrons tunnelling from the 2DEG, through a single QD. This is confirmed by the thermally activated onset of the tunnel current and the observation of Coulomb–Blockade in the reverse bias $I(V)$ [5]. Increasing the voltage across the device moves the energy of the dot ground state relative to the Fermi level of the 2DEG. Tunnelling occurs as the dot crosses the Fermi level of the 2DEG, and stops when the dot is brought below the 2DEG subband edge. Hence, the width of a feature seen in $I(V)$ is proportional to the Fermi energy of the 2DEG. In a current–voltage sweep we measure the voltage (V) dropped between the top and bottom contacts in the device. The voltage (V_d) dropped between the doped top contact layer and the dot is characterised by the electrostatic leverage factor, $f = V/V_d$, and this gives us an energy scale (eV_d) for the tunnelling process. As we are using 2D–0D tunnelling only the energy of the tunnelling electron is conserved, so the current we see at 4 K is proportional to the local density of states of the 2DEG adjacent to the dot.

At temperatures below 1 K the current onset becomes thermally activated and a sharp peak forms at the low-voltage side of the feature, as shown by the zero magnetic field curve in Fig. 2. This peak is strongly temperature dependent due to interactions between the fluctuating charge of the dot and electrons in the 2DEG, which allow tunnelling electrons to break energy conservation by transferring energy to or from other electrons in the 2DEG. The process is more efficient near the Fermi level, and for small-energy transitions, so we see an enhanced current at onset as the dot crosses the Fermi level, which falls away as the voltage is increased. This effect is termed a Fermi edge singularity (FES) [6].

Our measurements of the spin splitting were carried out on a dilution refrigerator, with the thermally activated onset indicating an electron temperature of ~ 100 mK, giving us an energy resolution of ~ 10 μeV. With a magnetic field applied parallel to the plane of the QDs, we follow the evolution of a current–voltage peak due to tunnelling through a single dot, as a function of the field. Fig. 2 shows $I(V)$'s at various fields between 0 T and 12 T. At fields between 4 and 10 T two fully resolved peaks can be seen, and the splitting between these peaks increases with the applied field. The voltage positions of these peaks versus B are shown in Fig. 3. As discussed in Ref. [5] the overall

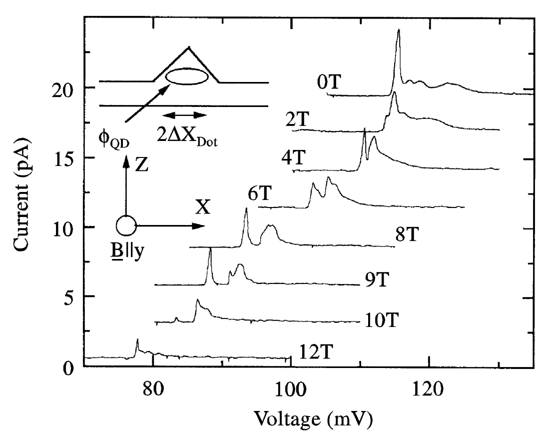

Fig. 2. Current–voltage sweeps taken at 40 mK, with magnetic field applied in the plane of the dots. The inset shows the orientation of the dot with respect to the field.

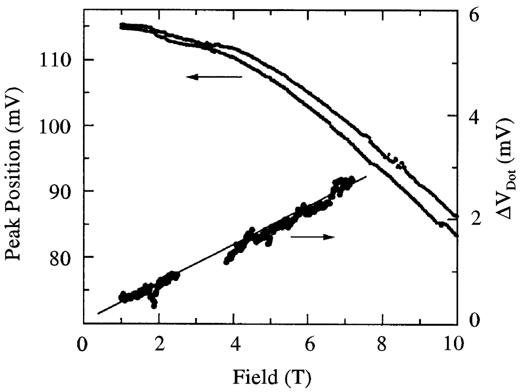

Fig. 3. Voltage positions and splitting (ΔV_{dot}) of the spin split peaks versus magnetic field. No voltage splitting values are plotted between 2.5 and 4 T, as the splitting is not clearly defined.

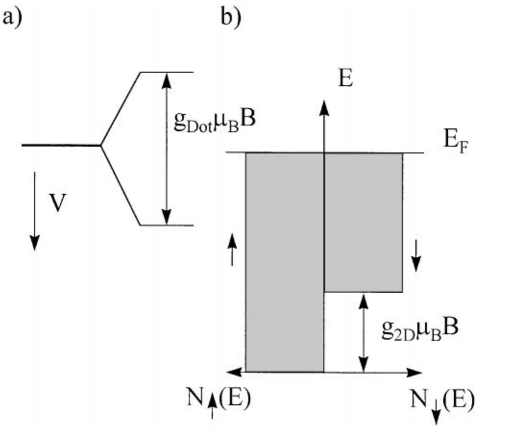

Fig. 4. Schematic diagram of the spin splitting in the InAs quantum dot (a), and of the 2DEG density of states showing partial spin polarisation (b). The effect of increasing the voltage across the device is to move the dot states down relative to the Fermi level of the 2DEG.

shift of peak position to lower bias with increasing field is due to the relative diamagnetic shifts of the 2DEG emitter state and dot state. From the diamagnetic shift we estimate the size of the dot to be 10 ± 5 nm, which is consistent with the average dot diameter observed using scanning tunnelling microscopy (STM) [5].

In a field the ground state of the QD splits into two spin energy levels given by

$$E_{\mathrm{Dot}} = g_{\mathrm{Dot}}\mu_{\mathrm{B}} B m_{\mathrm{S}} (m_{\mathrm{S}} = \pm 1/2). \quad (1)$$

This opens up two separate channels for electrons from the 2DEG to tunnel into (Fig. 4a), and we therefore see separate peaks in $I(V)$ due to electrons tunnelling through each of these spin energy levels. In a magnetic field applied parallel to the plane of the dots (i.e. parallel to the 2DEG) the 2DEG will become partialy spin polarised, due to an energy splitting of the Fermi energies of the two spin species. Due to the slow tunnelling rate from the 2DEG, the two spin species should be in thermal equilibrium, and so the chemical potential of each is the same. Therefore, there is an energy difference between the subband edge of the spin species, equal to the spin-splitting $g_{2\mathrm{D}}\mu_{\mathrm{B}}B$ (Fig. 4b). Tunnelling occurs as a dot spin level crosses the Fermi level of the 2DEG. For each spin we see a separate onset of tunnelling and the voltage difference between the positions of the onsets (ΔV_{Dot}) is proportional to the energy difference, $\Delta E_{\mathrm{Dot}} = g_{\mathrm{Dot}}\mu_{\mathrm{B}}B$, obtained from Eq. (1). The constant of proportionality is the electrostatic leverage factor, f ($f = 8.0 \pm 0.8$ at 115 mV), which is determined by fitting the Fermi function to the low voltage–current-onset at zero field [4]. Fig. 2 shows ΔV_{Dot} versus B. From the gradient of the line of best fit through these points we obtain a value for the magnitude of the g-factor of 0.82 ± 0.09.

We can gain information about the relative sign of the InAs QD and GaAs 2DEG g-factors from the ordering of the peaks in $I(V)$. Our argument is based on the assumption that spin is conserved in the tunnelling process. The first low-voltage peak seen in $I(V)$ at finite B is due to tunnelling through the low-energy spin level of the dot. It is the narrower of the two peaks, over a wide range of B. As can be seen in the schematic diagram in Fig. 4b, the energy spread of the two spin populations of the 2DEG is different. If this is the origin of the different peak width it implies that the lower-energy state of the dot corresponds to the spin orientation of the higher-energy state of the 2DEG. Therefore, the g-factor of the 2DEG and the dot must have opposite sign, i.e. if $g_{2\mathrm{DEG}}$ is negative, as for bulk GaAs, then $g_{\mathrm{Dot}} = +0.82$. We note that the g-factor for bulk InAs is $g = -14.8$. However, we expect

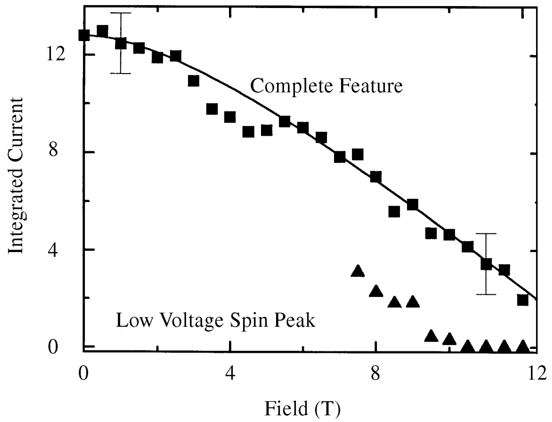

Fig. 5. Integrated area of the complete $I(V)$ feature, and the low voltage spin peak, versus magnetic field. Values for the low-voltage peak are only shown at fields where the two spin peaks in $I(V)$ are fully resolved.

g to be strongly modified for the QD, due to size quantisation, strain and other effects. Snelling et al. [7] observed a change in the sign of the g-factor of conduction band electrons in GaAs/AlGaAs quantum wells, as the well width was reduced. They discussed their results within the $\boldsymbol{k}\cdot\boldsymbol{p}$ model [8]. Using a simple three-band calculation given by Hermann and Weisbuch [8] we are able estimate the g-factor of an InAs dot to be $+0.26$ using a value for the energy difference between conduction and valence bands of 1.77 eV taken from PL measurements on similar dots in an AlAs matrix [9].

We now consider the magnetic field dependence of the amplitude of the tunnel current through the dot. This is shown in Fig. 5. At a field $B \geqslant 10$ T the lower bias peak in $I(V)$ vanishes. By increasing the temperature we are able bring this peak back, and at 12 T and 1 K the first peak is still present. At first sight this result indicates complete spin polarisation of the 2DEG above 10 T. However, it occurs at considerably lower field than would be expected from the sheet density of the 2DEG ($n_s = 0.5 \times 10^{11}$ cm^{-2} at 0.11 V) estimated from the magneto-oscillations for the other field orientation ($\boldsymbol{B} \| \boldsymbol{J}$) [10]. If the density were to remain roughly constant with field we would require a field of ~ 100 T to spin polarise the 2DEG, using a reasonable value [8] of the g-factor of the GaAs 2DEG. The disappearance of the low voltage–current peak due to spin polarisation may be evidence for a change of the character of the density of occupied states in the emitter 2DEG in high B.

We believe that the general fall in amplitude of both peaks with increasing B is due mainly to a well-established effect that can be understood in terms of a single-particle model for electrons tunnelling in the presence of a magnetic field. This effect is discussed in detail elsewhere [11–13]. For B applied perpendicular to the current direction, an electron tunnelling from 2DEG to QD acquires an additional in-plane (x–y plane) kinetic momentum ηk_0, given by $k_0 = eB\Delta s/\eta$, where Δs ($= 18$ nm for our device) is the effective distance between the 2DEG emitter accumulation layer and the QD [14]. The tunnelling rate from a 2DEG state of in-plane wavevector $\boldsymbol{k}$ into the QD is proportional to $|\phi_d(\boldsymbol{k})|^2$ where $\phi_d(\boldsymbol{k})$ is the Fourier transform of $\phi_d(x, y)$, the in-plane portion of the QD wave function, which we assume to be separable. Thus, by measuring the tunnel current as a function of B, and hence k_0, we can effectively map out the Fourier transform of the QD wave function [12]. From Fig. 5, the amplitude of the integrated tunnel current falls to half of its zero-field value at $B_{1/2} \approx 8$ T. Using the relation $\Delta x_{\mathrm{Dot}} = 1/\Delta k$ (with $\Delta s = 18$ nm), we estimate the lateral spatial extent of the dot wavefunction to be $2\Delta x_{\mathrm{Dot}} = 9$ nm (see inset to Fig. 1), in good agreement with independent estimates, given above, from the diamagnetic shift and STM data.

In summary we have observed tunnelling through the spin split ground states of a self-assembled InAs quantum dot. We measure the effective g-factor of the dot to be $+0.82 \pm 0.09$, compared to the g-factor of bulk InAs of -14.8. This enhancement of the g-factor is due to the confinement of electrons in the dot. For fields greater than 10 T the low-voltage spin-peak disappears. We are able to thermally excite the peak back by increasing the temperature to 1 K. This occurs at a lower field than would be expected for complete spin polarisation of the 2DEG. We also use magneto-tunnelling to estimate the spatial extent of the QD wave function (~ 9 nm).

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