Observation of spin splitting in single InAs self-assembled quantum dots in AlAs

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Using magneto-tunneling spectroscopy, we observe the Zeeman spin splitting of the ground state of a single InAs quantum dot grown within AlAs. We obtain values for the g factor of different quantum dots between $+0.52\pm0.08$ and $+1.6\pm0.2$, with magnetic field applied in the plane of the dot. This value for the g factor is considerably different from that of bulk InAs ($g=-14.8$), and we explain this using a simple three band $\mathbf{k}\cdot\mathbf{p}$ calculation. Using the spin split states of the dot as a probe, we observe the complete spin polarization of the emitter accumulation layer. © *1998 American Institute of Physics.* [S0003-6951(98)01329-1]

The spin splitting of the ground state of a single InAs self-assembled quantum dot (QD) is expected to be small (less than 1 meV at 10 T). Consequently, the direct observation of spin splitting using photoluminescence is difficult due to the broad distribution of dot ground state energies within a sample containing millions of dots. Similar remarks apply to measurements based on capacitance spectroscopy, although an average g factor of InAs QDs in an AlAs matrix has been obtained in this way.[1] The spin splitting of individual QDs formed by well-width fluctuations in a narrow GaAs/AlGaAs quantum well has been observed using microphotoluminescence.[2]

In this letter we use magnetotunneling spectroscopy to directly observe the spin splitting of single QDs, and to measure the g factor of the ground state of the dot. Our measurement technique is similar to that used to observe the spin splitting of donor impurity states within a quantum well.[3] Narihiro *et al.* observed tunneling through single InAs QDs, but the energy resolution of their results was not sufficient to allow the observation of spin splitting.[4]

We use a n-i-n GaAs/AlAs/GaAs single barrier tunneling device (see Fig. 1), where InAs QDs have been grown within the AlAs barrier using the Stranski–Krastanov growth mechanism. The dots are grown on top of 5 nm of AlAs, and are capped by a further 5 nm AlAs layer. Due to the size and structure of the dots, the amount of AlAs directly above the dots is less than 5 nm, introducing an asymmetry into the device (inset Fig. 1). The average dot diameter is 10 nm, and the average height is 3 nm, obtained using scanning tunneling microscopy and cross-sectional tunneling electron microscopy. The AlAs tunnel barrier is surrounded on either side by a 100 nm undoped GaAs spacer layer, and n-doped GaAs top and bottom contact layers. A more detailed sample description is given in Ref. 5. As a voltage is applied across the device, a two-dimensional electron gas (2DEG) accumulates in front of the AlAs barrier (see Fig. 1). We measure the tunnel current from the 2DEG through a single QD.[5] In forward bias, electrons tunnel into a dot through the thicker 5 nm AlAs barrier, and out through the thinner AlAs barrier (as shown in Fig. 1). Note that we measure the voltage dropped across the whole device (V) which is related to the voltage (V_1) dropped between the top contact layer and the dot by the electrostatic leverage factor, $f=V/V_1$.

At low temperatures the $I(V)$ characteristic in forward bias shows distinct peaks a few pA in height on a background current of less than 0.25 pA.[5] The low voltage onset of each peak is broadened by the Fermi distribution function at all temperatures down to 120 mK, implying that tunneling is through a single zero-dimensional state with linewidth <10 μeV. In reverse bias, charge buildup is possible and Coulomb blockade steps are observed in $I(V)$, indicating single electron charging effects and providing further evidence that tunneling is through a QD.[5]

The zero magnetic field $I(V)$ in Fig. 2 shows one of these peaks. The entire feature between 115 and 125 mV is due to tunneling from the emitter 2DEG through a single

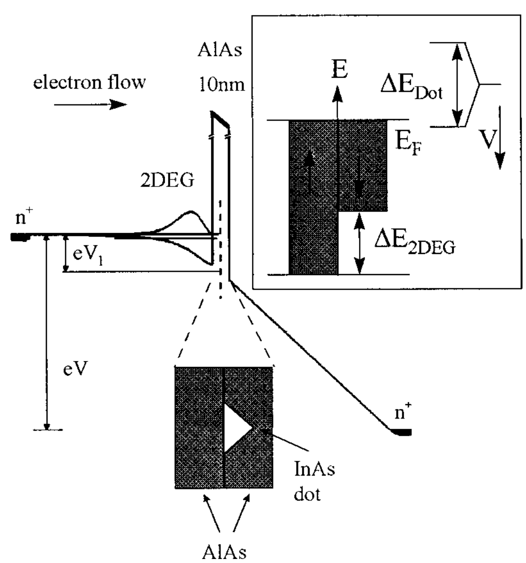

FIG. 1. Conduction band potential profile of the device under bias. The lower inset shows the orientation of a single dot in forward bias, and the upper inset a schematic diagram of the spin splitting in the dot and partial spin polarization of the 2DEG in a magnetic field. The effect of applying a voltage across the device is to move the dot energy levels down relative to the Fermi level of the 2DEG.

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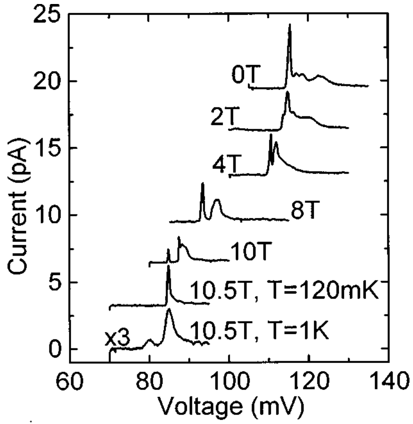

FIG. 2. $I(V)$ in a constant magnetic field. $T = 120$ mK except for the lowest which was taken at 1.0 K.

QD. The applied voltage alters the energy of the dot state relative to the 2DEG. Tunneling occurs as the dot state is brought resonant with the Fermi level, and continues as V increases until the dot ground state moves below the 2DEG subband edge. Consequently, the width of the feature divided by the electrostatic leverage factor is equal to the Fermi energy of the 2DEG. Below 1 K, a sharp peak forms at the low voltage edge of the feature, as shown in Fig. 2. This enhancement of the tunnel current is due to the formation of a Fermi edge singularity,[6] and is described in more detail elsewhere.[7] The structure at higher bias shows very little temperature dependence below 4 K, and is due to fluctuations in the density of states of the 2DEG local to the dot.[8]

The thermally activated current onset indicates an electron temperature in the 2DEG of ~120 mK, giving us an energy resolution of ~10 μeV. We follow the evolution of $I(V)$ with a magnetic field B applied in the plane of the dots, i.e., perpendicular to the current. Figure 2 shows $I(V)$ sweeps for B between 0 and 12 T. As B is increased the feature moves to lower voltage as a result of the relative diamagnetic shifts of the 2DEG and dot ground states.[5]

Above 1 T, the current onset splits and between 4 and 10 T the feature splits into two components. The splitting increases with increasing field, and is caused by the field breaking the spin degeneracy of the QD ground state, with an energy difference

$$\Delta E_{\mathrm{dot}} = g_{\mathrm{dot}} \mu_B B, \tag{1}$$

where g_{dot} is the g factor of the dot. The two peaks in $I(V)$ correspond to tunneling through the two spin states. As the field is increased the 2DEG becomes partially spin polarized, creating a difference in the Fermi energies of the two spin species. However, due to the slow tunneling rate, the two spin species in the 2DEG have a common chemical potential (see inset Fig. 1). The voltage difference ΔV_{dot} between the onset of tunneling through each spin level in the dot is then simply $f \Delta E_{\mathrm{dot}}$. There is no splitting at zero field within a resolution of 10 μeV.

Figure 3 shows the voltage positions of the onset of tunneling through each spin state, defined as the voltage where dI/dV is maximum, and ΔV_{dot} vs B. A straight line fit to the latter gives the magnitude of the g factor of this quantum dot as 0.82 ± 0.09. We use a value of 8.0 ± 0.8 for the leverage factor which is obtained either by fitting the Fermi function

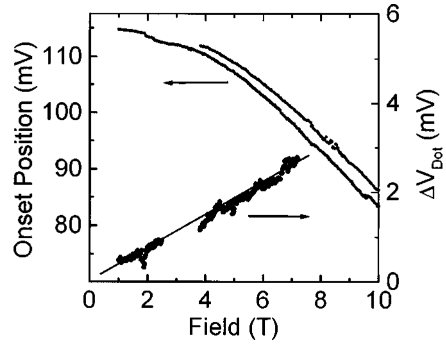

FIG. 3. Voltage positions and the splitting (ΔV_{dot}) of the onsets of the spin split peaks vs magnetic field. No values are plotted between 2.5 and 4 T, as the splitting is not clearly defined.

to the zero field current onset,[3] or from the Landau fan seen when B is applied parallel to the current,[5] both methods giving similar values. The uncertainty in our value of g is determined by the error in the leverage factor.

Assuming that spin is conserved in the tunneling process, we may obtain the sign of the g factor from the ordering of the peaks in $I(V)$. The lower voltage spin feature is due to tunneling through the lower energy spin level in the dot. Tunneling through this spin channel stops when the energy level moves below the subband edge of the corresponding spin species in the 2DEG. Hence the width of this peak is proportional to the Fermi energy of the spin species in the 2DEG. Similarly the voltage width of the second peak, caused by tunneling through the higher energy spin level, gives the Fermi energy of the other spin species (see inset Fig. 1). The lower voltage peak is consistently the narrower of the two, and hence has a smaller Fermi energy, indicating that the first peak corresponds to electrons tunneling from the higher energy spin species in the 2DEG through the lower energy dot spin level. This indicates that the g factors of the 2DEG and QD ground state have opposite sign. Hence, if the g factor of the GaAs 2DEG is negative, as in bulk GaAs,[9] the g factor of the InAs QD ground state is positive (i.e., $g_{\mathrm{dot}} = +0.82 \pm 0.09$). We have investigated several different dots with slightly different ground state energies, although all are in the low energy tail of the QD energy distribution. We obtain g factors between $+0.52 \pm 0.08$, and $+1.6 \pm 0.2$. Note that though the g factors of different dots are similar, their differences are well outside the error range. There appears to be no correlation between the g factor of a QD and the voltage at which the peak in $I(V)$ occurs, which is related to the ground state energy of the QD relative to the GaAs conduction band. These small values of g are similar to that obtained using capacitance spectroscopy,[1] and are very different to the g factor of bulk InAs ($g = -14.8$).

We expect the g factor of the InAs QDs to be different to bulk InAs due to size quantisation, strain, and other effects. Snelling *et al.*[9] observed a change in the sign of the g factor for electrons in a GaAs/AlGaAs quantum well as the well width was reduced. They explained their results within a **k·p** model. To estimate the g factor in our dots we use a simple three-band model given by Hermann and Weisbuch[10]

$$\frac{g^*}{g_0} - 1 = -\frac{P^2}{3}\left(\frac{1}{E_0} - \frac{1}{E_0 + \Delta_0}\right), \tag{2}$$

where $g_0=2$, $P^2=22.2$ eV is the coupling matrix element for InAs, $\Delta_0=0.38$ eV is the valence band spin-orbit splitting for InAs, and E_0 is the energy gap between conduction and valence band states. In Eq. (2), following Snelling *et al.*,[9] we have taken E_0 as the energy difference between the confined electron and hole states in the QD. Using a reasonable value for E_0 of 1.77 eV for dots in AlAs,[11] we obtain $g\approx+0.26$. The model provides a semiquantitative explanation of the change in sign of the g factor. Additional effects will be due to strain in the dots and wave function penetration into the barrier. An exact calculation of the g factor would only be possible with detailed knowledge of the size, shape, and composition of the specific dots.

It is also possible to investigate the spin properties of the 2DEG with a field applied in the plane of the dots. At a sample temperature of 120 mK and magnetic fields above 10.2 T, the lower voltage peak disappears, as shown in Fig. 2, but we are able to regain this peak by thermal activation, indicating that the disappearance of the peak is due to the complete spin polarization of the 2DEG (Fig. 2). From the thermal activation we are able to estimate the magnitude of the g factor of the 2DEG to be approximately 0.5. This value of g is also consistent with the relative peak widths prior to spin polarization. However, given the density of the 2DEG at zero field ($n_s=0.5\times10^{11}$ cm^{-2} at 0.11 V) estimated from the magneto-oscillations seen in $I(V)$ when the field is applied parallel to the current,[12] we expect to require a field of around 100 T to spin polarize fully the 2DEG. The results indicate either a global or local reduction in the density of the 2DEG, or a narrowing of the 2DEG density of states, when a strong in-plane magnetic field is applied. Further work is required to explain the origin of this discrepancy. However, the linearity of ΔV_{dot} vs B in Fig. 3 indicates that the electrostatic leverage factor remains constant over the field range of interest.

In conclusion we are able to observe directly the spin splitting of the ground states of single InAs quantum dots. We can measure the g factor of the dots, and obtain values between $+0.52\pm0.08$ and $+1.6\pm0.2$.

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