ELSEVIER

Physica B 256–258 (1998) 507–513

PHYSICA B

Magneto-tunnelling spectroscopy of a two-dimensional electron system

P.C. Main *, A.S.G. Thornton, T. Ihn [1], L. Eaves, K.A. Benedict, M. Henini

Department of Physics, University of Nottingham, Nottingham, NG7 2RD, UK

Abstract

We use a single, InAs self-assembled quantum dot to probe the local density of states of a two-dimensional electron system (2DES) at all energies from the sub-band edge to the Fermi energy. The dot is incorporated as part of an AlAs barrier in a single barrier tunnel diode. Variation of the bias across the device changes the energy of the dot ground state relative to the 2DES. For magnetic field, B, applied parallel to the current, we observe peaks in the current–voltage characteristic, $I(V)$, corresponding to the formation of Landau levels (LLs) in the 2DES although the lowest energy levels are not well resolved at low B due to the effect of the quasiparticle lifetime. At higher B, at filling factor $\nu = 1$ and beyond, we observe a number of effects. First, we observe directly the exchange enhancement of the Landé g-factor; the lower energy spin polarised LL moves to lower energy with increasing B. Second, close to $\nu = 1$, the current from the lowest LL is suppressed although the current is restored as the temperature, T, is increased from 100 mK to 2 K. Finally, for $\nu \leqslant 1$, reproducible fine structure appears in $I(V)$, which is very sensitive to both B and T. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Tunnelling; Quantum dot; Landau levels; Many-body effects

Conventional magnetotransport measurements on two-dimensional electron systems (2DES) are sensitive only to effects at the Fermi energy, ϵ_F. In this paper, we demonstrate the use of a single quantum dot (QD) to probe the local density of states (LDOS) of a 2DES for all energies between ϵ_F and the subband edge. When a magnetic field, B, is applied parallel to the current direction, the current through the dot splits into a series of peaks, reflecting the Landau levels (LLs) in the 2DES. Our technique then allows us to probe the LLs at all energies as a function of filling factor, ν. Although there have been many experiments investigating tunnelling through quantum dots [1], most of these have been in the linear regime and have been concerned with the properties of the dots themselves. The use of a localised state to probe continuum states has been investigated in disordered systems [2,3] but, to our knowledge, no one has been able to resolve clearly the LLs. In our experiment, the well-defined character of the QD with a very narrow bandwidth of the ground state, <10 μeV, makes possible sensitive spectroscopy of the 2DES.

Our devices consist of a 10 nm AlAs tunnel barrier separated from graded n-type top and bottom contacts by 100 nm undoped GaAs spacer layers. InAs quantum dots were grown on the centre

---

* Corresponding author. Fax: +44 115 951 5180; e-mail: peter.main@nottingham.ac.uk

[1] Present address: Solid State Physics Laboratory, ETH Hoenggerberg, CH-8093 Zurich, Switzerland.

PII: S 0 9 2 1 - 4 5 2 6 (9 8) 0 0 5 7 3 - 0

plane of the barrier using the Stranski–Krastonow growth mode, producing a dot density of $\sim 2 \times 10^{15}$ m^{-2} with a typical size ~10 nm. A detailed description of the devices can be found in Ref. [4]. When a bias is applied across the device, a 2DES forms in an accumulation layer in front of the AlAs barrier (see Fig. 1(a)). Increasing the applied voltage, V, reduces the energy of the QD states relative to the 2DES. When a particular dot state is resonant with the 2DES, electrons may tunnel in and a current will flow. Therefore, as we adjust the voltage we expect to see a step change in the current, limited only by the k_BT smearing of the Fermi function, as the dot state becomes resonant with the 2DES Fermi level. Since the emitter electron density varies roughly linearly with V, by choosing dots with different ground state energies, we are able to probe 2DES over a range of electron density.

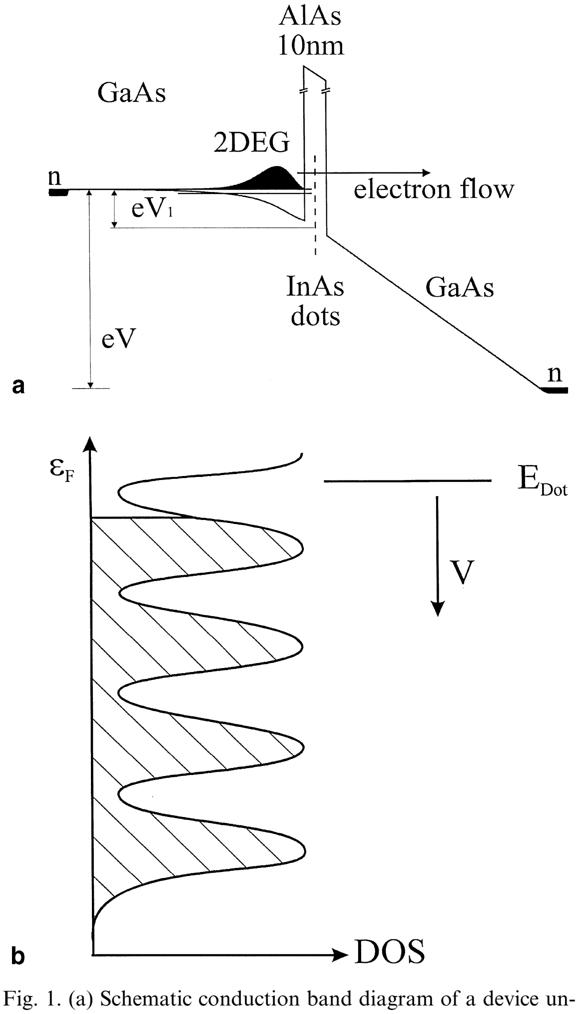

Fig. 1. (a) Schematic conduction band diagram of a device under bias. The leverage factor, f, is defined as V/V_1. (b) Schematic illustration of the effect of V in shifting the energy of the dot state relative to the 2DES. The number of filled LL is determined by the applied magnetic field.

Typical low-temperature $I(V)$ curves near the current onset of a 5 μm diameter mesa are shown in Fig. 2. Measurements were made using standard DC techniques. We define forward bias as the direction in which the electrons tunnel through the 5 nm AlAs barrier before entering the dot. The barrier on the other side of the dot is much smaller due to the finite height of the dot, so in forward bias the dot remains empty for most of the time and the current is determined by the rate at which the electrons tunnel in. The initial current onset of the curves in Fig. 2 is thermally activated down to ~100 mK, which indicates that the feature is due to tunnelling through a state associated with a single dot. Additional evidence is provided by the existence of Coulomb blockade steps in reverse bias. This is discussed further in Ref. [4]. Although there are ~40 000 dots in the device, most have

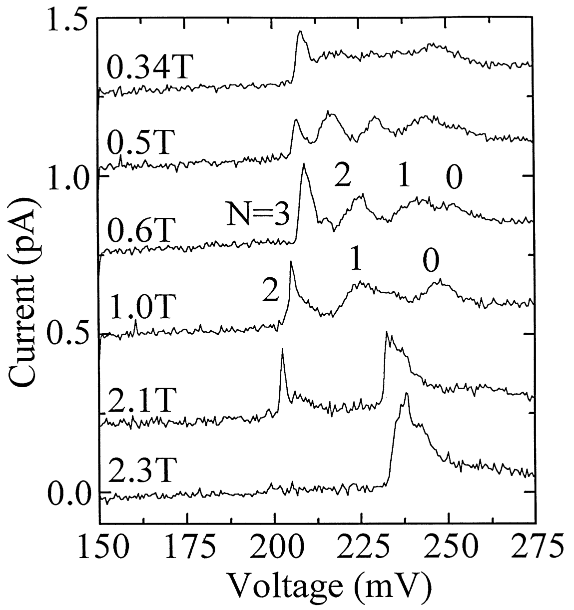

Fig. 2. $I(V)$ at various B at a nominal temperature of 100 mK. $N = 0$, 1 etc. refer to LL indices. Curves are offset for clarity.

their electron ground state energies above the GaAs conduction band edge and hence above the Fermi energy of the 2DES. The individual dot we observe is at the low energy edge of the distribution of sizes. In the $B=0.38$ T curve of Fig. 2, the QD is resonant with the Fermi energy of the 2DES at 205 mV and the sub-band edge at 260 mV, corresponding to a Fermi energy of 3.8 meV after taking into account the electrostatic leverage factor $f\sim 14.4$ (see below) which relates the applied voltage to the energy difference between the dot levels and the 2DES. An important feature of our experiment is that, because we tunnel through a single dot, we are able to scan the entire Fermi energy with a single *spectrometer* state.

The peak in $I(V)$ at the current onset of the curves in Fig. 2 is a Fermi edge singularity (FES), previously observed in tunnelling from a 2DES through an impurity state in a quantum well [5]. In the device of Fig. 2 it is rather weak and is much more pronounced in other devices. The behaviour of the FES in a magnetic field is discussed elsewhere in these proceedings [6]; in this paper, we concentrate on the current at voltages beyond the FES where we believe the current is principally determined by the density of states in the 2DES [3]. Narihiro et al. [7] have also reported tunnelling through a single QD but they do not observe a thermally activated current onset and, consequently, interpretation is more complicated. For all the dots in our experiment, the current onset was thermally activated down to ~100 mK, indicating the small energy linewidth of the QD state. In fact, this saturation of the onset activation is due to the problem of cooling the 2DES, which is severe in a device of this type, and does not represent the true linewidth of the state. The localised character of the dot state means that the tunnel current is very insensitive to the electron k-vector and we may assume that the tunnelling probability is not dependent on energy [8]. The sharp onset has also enabled us to measure the spin splitting of the QD ground state [9] in B applied perpendicular to the current. We find that the Landé g-factor appropriate for the electron ground state of the InAs dot has a value around +1, quite different from the value of −14.6 appropriate for bulk InAs, reflecting the effect of the quantum confinement.

Fig. 2 shows $I(V)$ at various B applied parallel to the current. The operation of the spectrometer in this regime is shown schematically in Fig. 1(b). The magnetic field determines which LLs are occupied and the voltage shifts the energy of the dot state relative to the 2DES. For the device of Fig. 2, above 0.4 T we observe well defined LLs as shown, for example, in the curve for 0.6 T. Interestingly, no LLs are resolved at all for $B<0.4$ T but at 0.42 T and above, the $N=2$, 3 and 4 levels are clearly resolved. The sudden appearance of well-resolved, higher order LLs at 0.42 T indicates a scattering time, τ, of 1×10^{-12} s and a corresponding 2DES mobility $\mu\sim 2.5$ m^2 V^{-1} s^{-1}. Note that the two lowest LLs, $N=0$ and $N=1$ are not resolved in this range of B. A possible reason for this is that at energies well below ϵ_F, the quasiparticle lifetime τ_{qp} may become so short that $\omega_c\tau_{qp}<1$, where $\omega_c=eB/m^*$ is the cyclotron frequency with m^* the effective mass. At 0.4 T this condition corresponds to $\tau_{qp}=10^{-12}$ s, which is a reasonable value for a state of energy $\sim\epsilon_F/2$ according to a Fermi golden rule calculation [10] which predicts $\hbar/\tau\sim(E-\epsilon_F)^2/\epsilon_F$. At higher $B\sim0.6$ T, the $N=0$ and $N=1$ LLs are just resolved as their degeneracy increases and they move to higher energy. At 2.1 T, the chemical potential of the 2DES lies within the $N=1$ LL and the $N=0$ spin degenerate level is fully occupied. In the lowest curve, at 2.3 T, the chemical potential lies in the gap between the $N=0$ and the $N=1$ LLs and only the $N=0$ spin-degenerate LL is occupied. Note that we cannot resolve any spin splitting within the LL at this field.

Fig. 3 shows a fan diagram of the main peak positions corresponding to LLs lying below the chemical potential in the 2DEG. Where the chemical potential lies in the mth level, we plot only the peak position of the levels up to $(m-1)$. Note that as each LL increases its energy with increasing B as $E_N=(N+1/2)\hbar\omega_c$, each peak moves to lower voltage. The values of $(N+1/2)\hbar\omega_c$ for $N=0$ to 4 are drawn as solid lines assuming an effective mass $m^*/m=0.07$ and that the sub-band edge is at 260 mV. The leverage factor $f=14.4$ is obtained by assuming that the current onset is thermally activated [11]; effectively, k_BT is used as an energy calibration. It is not straightforward to calculate f from

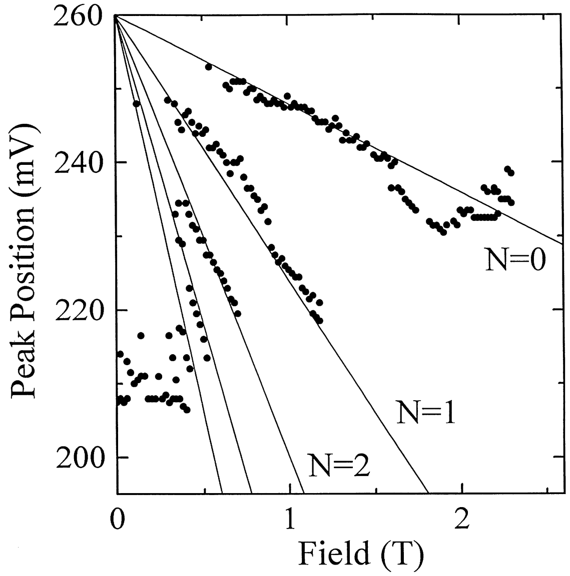

Fig. 3. Peak positions in $I(V)$ versus magnetic field. The lines are the expected energies of the LLs.

the electrostatics of the device due to the effect of the charging of the QDs in the barrier. The fan plot confirms the identification of the peaks in $I(V)$ with LLs and shows that the LL splitting is $\hbar\omega_c$ over a large range of filling factor, in agreement with recent measurements [12] of the chemical potential discontinuity at integer filling factors. The deviation of the data from linearity above 1.7 T for the $N = 0$ line is due to structure appearing in the peak in $I(V)$. The points for $B < 0.4$ T are not LL but are due to mesoscopic fluctuations in the LDOS [3] and will be discussed elsewhere. We may also calculate n from the depopulation fields of the LLs; we find $n \sim 1.2 \times 10^{15}$ m^{-2}, corresponding to $\epsilon_F = 4$ meV, consistent with the estimate above from the $I(V)$ curve at low B and the measured value of f. Over a range of B, we are also able to determine the LL widths [13]. This is problematic since the LL shapes are not gaussian and are rarely symmetric. However, a systematic feature is that, at a given B, the $N = 1$ LL appears broader than the $N = 0$ LL. See, for example, the 1.0 T curve in Fig. 2.

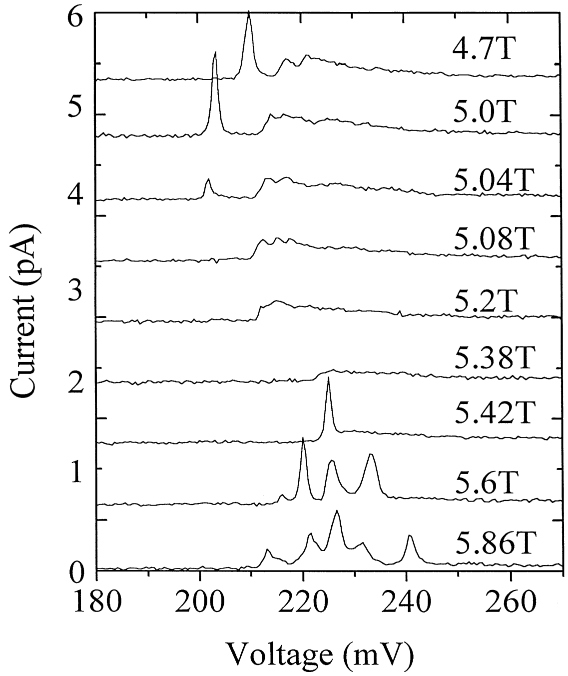

Fig. 4. $I(V)$ at various B in the vicinity of $\nu = 1$ for the device of Fig. 2. Curves are offset for clarity.

Fig. 4 shows data in the vicinity of $\nu = 1$, where the chemical potential enters the energy gap between the two spin-split components of the lowest LL. At 4.92 T, the sharp peak in the current at 205 mV is as FES due to tunnelling through the higher energy, spin-polarised LL. There is a region of near-zero current corresponding to a gap in the density of states, then the current rises again around 215 mV to form a broad peak as the dot state probes the states in the lower level. This gap in the density of states would not be measurable in a linear conductance measurement at this filling factor but it is roughly analogous to the mobility gap measured by thermal activation of the longitudinal resistance at $\nu = 1$. Note that it is very difficult to assign filling factors unambiguously in this region. For all fields between 5.06 and 5.4 T, the chemical potential local to the dot lies between the spin-polarised LLs, presumably pinned in some part of the device remote from the QD probe. Also, it is very difficult in our experiment to measure the magnetically-induced energy gap observed in 2D–2D tunnelling experiments [14]. Around 5.06 T, the chemical potential passes out of the upper level; this has two striking effects on the current. First, the current onset shifts rapidly to *higher* voltage, i.e. the lower spin state moves to *lower* energy, with increasing *B*. This should be contrasted with the monotonic decrease of onset voltage seen at other *B* (see Fig. 3) and is a *direct* observation of the enhancement of the spin splitting due to exchange effects [15].

From the decrease in energy of the current onset relative to the expected increase as $\frac{1}{2}\hbar\omega_c$, we are able to calculate the variation of the effective Landé *g*-factor of the 2DES, g^*, with *B*, which is shown in Fig. 5. The principal source of systematic uncertainty is in determining the leverage factor, but there is also a contribution from the diamagnetic shift of the dot ground state [9]. We estimate the values of g^* are accurate to ±1. Dolgopolov et al. [12] obtained $g^* = 7$ at $\nu = 1$ using a capacitance technique to measure the shift in chemical potential at $\nu = 1$. This value is consistent with our results, but their technique did not allow them to see the variation of g^* with *B*. Values of g^* obtained from another device, where $\nu = 1$ occurs at around $B = 3$ *T*, are also shown in Fig. 5. In this case, the data are shown as a continuous line representing the locus in *V* of the current onset as *B* varies. The similarity of the data indicate that, in agreement with Dolgopolov et al. [12], the exchange-enhanced spin splitting is proportional to *B*, i.e. g^* is not dependent on *B*. Note that the measurements were performed on 2DES systems with different degrees of disorder.

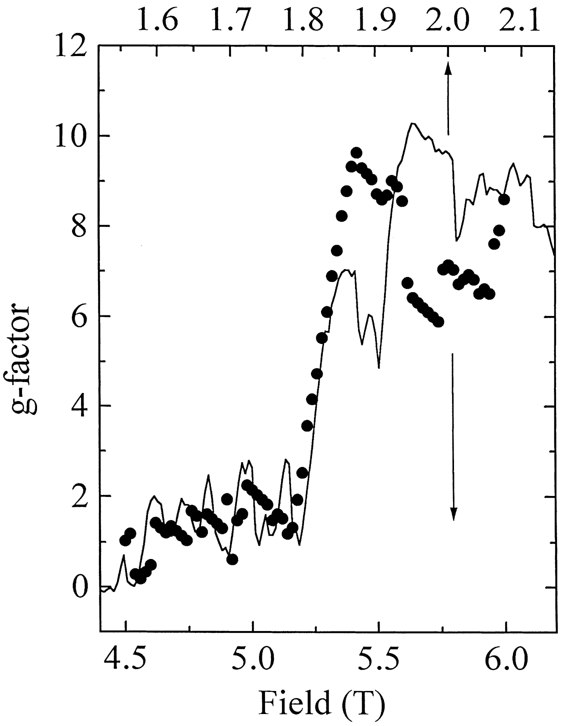

Fig. 5. Effective Landé *g*-factor of the 2DES versus *B* for two devices near $\nu = 1$. The lower and upper *B* axes refer to the discrete points and the continuous curve respectively.

The second phenomenon which occurs around $\nu = 1$ is that the current from the lower spin channel is suppressed. At 5.4 T and $T = 100$ mK, the total integrated current from the lower energy, spin polarised LL is 40% of its value at 4.7 T when the chemical potential is in the upper level and the number of electrons in the lower level is ~14% lower due to the change in degeneracy with magnetic field. The variation of the integrated current from the lowest spin polarised LL is shown in Fig. 6 for two temperatures. The quenching of the

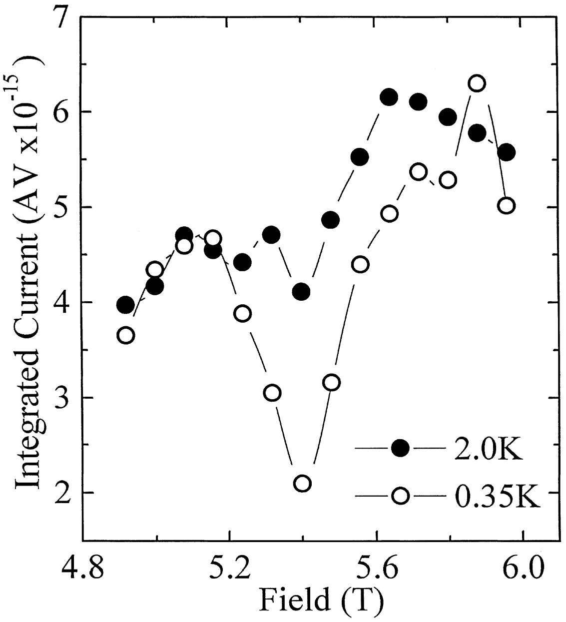

Fig. 6. Total integrated current from the lower energy, spin-polarised LL versus magnetic field in the vicinity of $\nu = 1$ at two temperatures.

current around $\nu = 1$ disappears with increasing T and above 2 K the integrated area is independent of B and T. The quenching of the current at low temperatures shows that when the $N = 0$ spin polarised LL is completely filled, it is very resistant to losing a single electron. Around $\nu = 2$ there is no similar effect and the current in the $N = 0$ spin degenerate LL is approximately independent of B when the chemical potential lies in the gap between it and the $N = 1$ level. In addition, there is a qualitative difference between the T dependences of $I(V)$ at the two filling factors ($\nu = 1$ and $\nu = 2$) as shown in Fig. 7. In Fig. 7(a), the chemical potential is between the $N = 0$ and $N = 1$ LL (this is a different device to the one shown in Fig. 2). The onset is not broadened by temperature, exactly as one would expect for a completely filled LL with $\hbar\omega_c \gg k_B T$. There are no states local to the dot into which the electrons may be thermally excited.

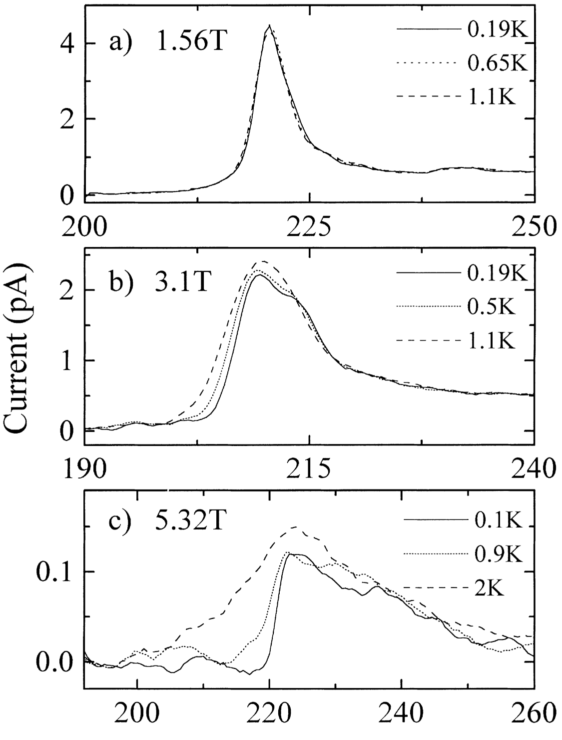

Fig. 7. $I(V)$ versus magnetic field at various temperatures near (a) $\nu = 2$, (b) $\nu = 1$ in the same device and (c) $\nu = 1$ in the device of Fig. 2.

Fig. 7(b) shows $I(V)$ at various T for the same device as Fig. 7(a) but when the chemical potential is in the energy gap between the spin polarised levels, just above the lower energy, spin polarised LL. Fig. 7(c) shows the same curves for the device of Fig. 2. For the two devices, this corresponds to magnetic fields of 3.1 and 5.32 T respectively, approximately equivalent to $\nu = 1$. The behaviour is quite different to that shown in Fig. 7(a); increasing T leads to an additional current at voltages below the low temperature current threshold. This temperature dependence is unique to $\nu = 1$ and is qualitatively different from that at any other filling factor. It is easy to see that the increase with temperature of the integrated $I(V)$, apparent in Fig. 6, is a direct result of the behaviour shown in Fig. 7(b) and (c).

There are no existing theories which provide an adequate description of either the suppression of the current at $\nu = 1$ or the anomalous temperature dependence. The latter might be interpreted as a temperature dependent spin gap [16] but this should only be apparent when the polarisation of the 2DES is itself temperature dependent, which is most certainly not the case in our experiment. The suppression of the current itself may be because the low-lying excitations of the 2DES are collective modes [17] which produce a barrier to single carriers tunnelling from the 2DES when the polarised LL is completely full. However, it is difficult to see why the current is suppressed over the whole LL, even when the dot energy is well below the Fermi energy of the 2DES.

Fig. 4 also shows how $I(V)$ varies when the chemical potential enters the spin-polarised LL. Initially ($B = 5.4$ T) there is a rapid increase in current at the onset. At slightly higher fields, the LL breaks up into well defined peaks. As B is increased further, the pattern of the peaks changes rapidly and the voltage range over which we observe a current increases. Furthermore, the temperature dependence of the extra structure is unusual. Whereas, in general, the effect of temperature is usually confined to within a few $k_B T$ of the current onset, in this regime, approximately from $\nu = 1$ to $\nu = 0.85$, individual peaks at any voltage are strongly dependent on

T. Also, whereas some of the peaks grow with decreasing T, others grow with *increasing* T. We have no model for the existence of this structure or its strange temperature dependence. Although Shahbazyan and Ulloa [18] have recently predicted the existence of sub-LL structure in the presence of resonant scattering, their model is not applicable to our system where we have only one state resonant with the 2DES during the measurement.

The sharp structure in $I(V)$ persists to $\nu \sim 0.85$. At higher B the $I(V)$ curves become only weakly dependent on B. The limiting high field behaviour is an initial FES peak at the current onset, followed by a single, or occasionally double, peak has been seen in the $I(V)$ of many individual dots in several devices. It is reminiscent of the $I(V)$ curve predicted for tunnelling between two 2DES in a similar field regime in the presence of skyrmions [19], although, to our knowledge, there has been no calculation of 2D to 0D tunnelling in this regime.

In summary, we have used the discrete ground state of a quantum dot as a spectroscopic probe of a 2DES in a magnetic field. This allows the *direct* observation of the density of states variation due to the formation of Landau levels and the exchange enhancement of the spin splitting when $\nu = 1$. We also observe a number of qualitatively new phenomena which may not be readily explained within a single-particle picture.

Acknowledgements

This work is supported by EPSRC(UK). LE wishes to thank EPSRC(UK) for financial support. We are grateful to Boris Muzykantstkii for helpful discussions.

References

[1] See, for example, L.P. Kouwenhoven et al., in: L. Sohn et al. (Eds.), Mesoscopic Electron Transport, NATO ASI Ser. E, Kluwer Academic Publishers, Dordrecht, 1997.
[2] U. Sivan et al., Europhysics Lett. 25 (1994) 605.
[3] T. Schmidt et al., Phys. Rev. Lett. 78 (1997) 1540.
[4] I.E. Itskevich et al., Phys. Rev. B 54 (1996) 16401.
[5] A.K. Geim et al., Phys. Rev. Lett. 72 (1994) 2061.
[6] K.A. Benedict et al., in these Proceedings, Physica B 256–258 (1998) 519.
[7] M. Narihiro et al., Appl. Phys. Lett. 70 (1997) 105.
[8] T.M. Fromhold, F.W. Sheard, L. Eaves, Acta Phys. Polon. B 82 (1992) 737.
[9] A.S.G. Thornton et al., Appl. Phys. Lett., July 1998.
[10] D. Pines, P. Nozières, The Theory of Quantum Liquids, Vol. 1, Addison Wesley, Reading, MA, 1989, p. 309.
[11] M.R. Deshpande et al., Phys. Rev. Lett. 76 (1996) 1328.
[12] V.T. Dolgopolov et al., Phys. Rev. Lett. 79 (1997) 729.
[13] A.S.G. Thornton et al., Physica B 249–251 (1998) 689.
[14] J.P. Eisenstein et al., Phys. Rev. Lett. 69 (1992) 3804; R.C. Ashoori et al., Phys. Rev. Lett. 64 (1990) 681.
[15] T. Ando, Y. Uemura, Phys. Rev. 174 (1974) 1044.
[16] A. Usher et al., Phys. Rev. B 41 (1990) 1129.
[17] S.L. Sondhi et al., Phys. Rev. B 47 (1993) 16419.
[18] T.V. Shahbazyan, S.E. Ulloa, Phys. Rev. Lett. 79 (1997) 3478.
[19] J.J. Palacios, H.A. Fertig, Phys. Rev. Lett. 79 (1997) 4712.