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Many-body effects in a quantised 2DES probed by discrete-level tunnelling spectroscopy

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Abstract

We use the discrete state of a self-assembled InAs quantum dot for tunnelling spectroscopy of the local density of states of a 2DES over the full-energy range from the Fermi energy, E_F, to the subband edge. In a magnetic field, B, applied parallel to the current we observe the formation of Landau levels and measure their width as a function of B. When the dot state is resonant with E_F, we observe a Fermi-edge singularity in the current which enables us to study many-body effects in a magnetic field. © 1998 Elsevier Science B.V. All rights reserved.

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Conventional magnetotransport experiments in 2D electron systems (2DES) are sensitive only to the properties of the electrons at the Fermi energy, E_F. Tunnelling between parallel 2DES [1,2] provides some information about electrons below the Fermi level but, inevitably, there is always spatial averaging over the area of the 2DES. In this paper we describe a technique of tunnelling from a 2DES into a single-energy state of a 0D quantum dot (QD). This allows us to probe directly the electron states between E_F and the subband edge. The technique is a probe of the local density of states (LDOS) of the 2DES. In addition we are able to study many-body effects in the form of the Fermi-edge singularity (FES) [3] in the tunnel current which occurs when the dot state is resonant with E_F.

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 QDs were grown in the centre of the barrier using the Stranski–Krastanow growth mode, with a dot density of $\sim 2 \times 10^{11}\ \mathrm{cm}^{-2}$, and typical dot sizes of $(10 \times 10)\ \mathrm{nm}^2$. A detailed description of the samples can be found in Ref. [4]. When a bias is applied across the device, a 2DES forms in front of the AlAs barrier (Fig. 1). By changing the applied voltage we move the ground state of the QD relative to the Fermi level of the 2DEG. When the 0D energy level is resonant with an occupied electron state in the emitter, a current flows. The voltage at which features occur in $I(V)$ depends upon the

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ground-state energy of the particular QD. Since the emitter electron density varies with the applied voltage, by choosing dots with different ground-state energies we are able to probe 2DEGs over a range of densities. Measurements were carried out on a dilution refrigerator with a base temperature of 30 mK using standard DC techniques.

Fig. 2a shows the temperature, T, dependence of a feature due to tunnelling through a single QD. At low temperatures the current onset at 115 mV (where the 0D state is resonant with E_F) forms a sharp peak which is strongly temperature dependent. At higher voltage the trace exhibits only a weak temperature dependence [3,5]. This enhancement of tunnelling current is termed a Fermi-edge singularity (FES), and has been seen previously in experiments on tunnelling through donor states of a quantum well [3]. Fig. 2b shows the integrated tunnel current $\int_0^V I(V_1)dV_1$, as a function of V and has three remarkable features all of which confirm the many-body character of the FES. First, the total integrated area is dependent on T which would not be true for a simple kT smearing of the onset. In that case, the curves corresponding to the various T would all merge at sufficiently high V. Second, the effect of T persists to energies well below the onset. Third, the integrated current curves all cross at a single point which corresponds to the voltage of the FES peak (note that it is *not* the same voltage as the crossing point in $I(V)$). Although there has been some theoretical discussion of the FES in zero magnetic field [6–8], to date there appears to be no description of either the functional form of our FES or its T dependence. Experimentally, there are variations in the strength of the FES from dot to dot, indicating differences in the strength of the interaction between the dot and the 2DEG.

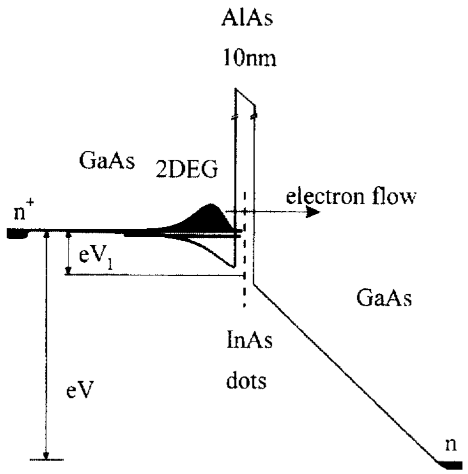

Fig. 1. Conduction band profile of the device under bias. The electrostatic leverage factor is defined as dV/dV_1.

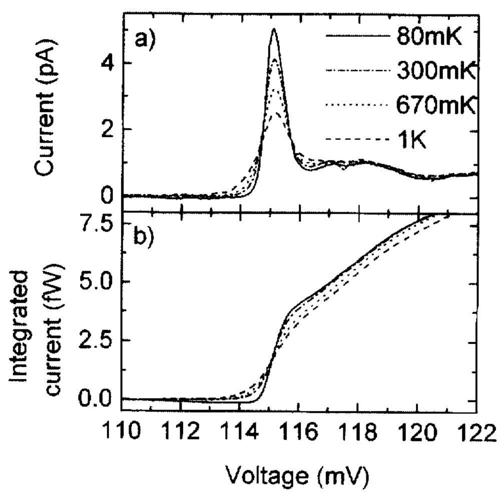

Fig. 2. Temperature dependence of (a) $I(V)$ in zero field, and of (b) the integrated tunnel current versus voltage.

To study many-body effects at and around the Fermi energy we follow the onset voltage V_F and the FES peak current in a magnetic field. The onset voltage is defined as the voltage at which the tunnelling current through the dot first exceeds 1 pA (using a different value does not greatly affect the results). The voltage across the device is roughly proportional to n_s in the emitter accumulation region ($V \approx n_s e/C$, where C is the device capacitance). Therefore, a variation in V_F reflects the variation in n_s which, in turn, is a consequence of the requirement that the 2DES chemical potential is equal to that of the contact. Consequently, as the LL filling factor changes in the 2DES electrons move between it and the n^+ contact layer to maintain this equality.

Fig. 3 shows a plot of the onset voltage V_F, and the FES peak current for a sample in which the FES is the dominant contribution to the current at

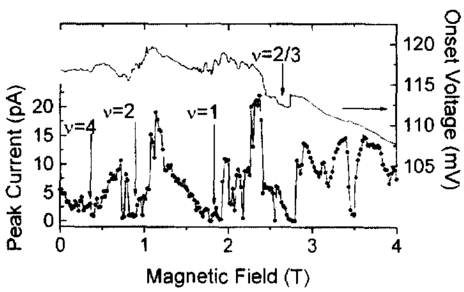

Fig. 3. Onset voltage and FES peak current versus magnetic field at $T = 100$ mK.

zero field. The fine structure on the curve is entirely reproducible. As expected, as LLs depopulate, V_F exhibits $1/B$-periodic oscillations, from which we obtain the filling factor, ν, and hence n_s. At higher fields, we see a continuous fall in V_F as the chemical potential is pinned in the lowest LL, for which the energy increases as $\hbar\omega_c/2$. In addition, we see a feature at $\nu = \frac{2}{3}$; this will be explored in a future paper.

The FES peak current shows minima at filling factors 1, 2 and 4. In order to estimate where there will be a FES and how it will affect the shape of the tunnelling characteristics we have calculated the tunnel current assuming Gaussian LLs and including the final state interaction (within a simple approximation). The qualitative form of the tunnelling characteristics agrees well with the experiment. As in the case of the X-ray problem [9], the form of the singularity is

$$I(E_d) \sim (E_F - E_d)^{-\Omega\rho(E_F)U}, \quad E_d < E_F,$$

where E_F is the Fermi energy, E_d is the energy of the dot, Ω is the area of the 2DES, $\rho(E_F)$ is the (local) density of states at the Fermi energy and U is the strength of the interaction between the dot and the 2DES, which, of course, depends on the density of states at the Fermi level through the screening. This indicates that when the Fermi edge lies in the centre of a Landau level there is a strong enhancement of the tunnel current. When the Fermi energy lies in the tail of the Landau level there is no such enhancement, despite the relative inefficiency of the screening. The collapse of the peak current at 3.5 T in Fig. 3 occurs almost precisely at $\nu = \frac{1}{2}$ and is a feature of some but not all the tunnelling $I(V)$ for the various samples we have studied.

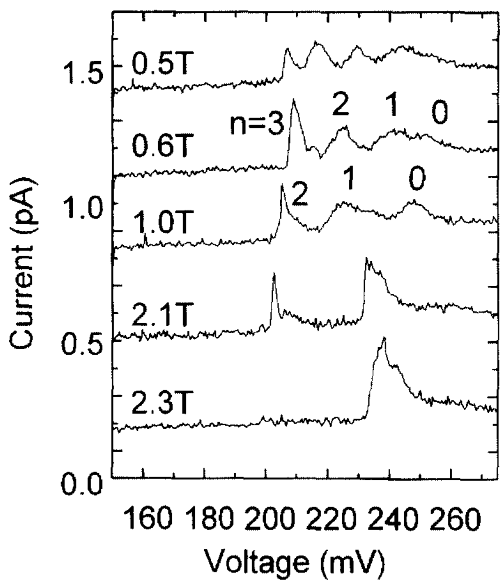

Fig. 4. $I(V)$ at $T = 100$ mK for B between 0.5 and 2.3 T, showing the development of the Landau levels.

At voltages beyond the FES, the current is a direct measure of the LDOS of the 2DEG adjacent to the dot. With a magnetic field applied parallel to the current, distinct peaks develop in $I(V)$ due to the formation of Landau levels (LLs). Fig. 4 shows $I(V)$ sweeps in a field for one of the dots studied. The zero-field current onset, at approximately 200 mV, shows only a weak FES and the band edge is at 260 mV. LLs close to the Fermi energy are well resolved, for example, the peaks labelled 2 and 3 in the 0.6 T trace. However, near the bottom of the emitter subband, the LLs become indistinct. The $n = 0$ and 1 LLs are barely distinguishable in the 0.6 T trace, and not at all in the 0.5 T trace. At higher fields, as they approach E_F, they become better resolved. Where the LLs are distinct, the splitting is $\hbar\omega_c$ (using a leverage factor, f, of 14 obtained from the temperature dependence of the onset). This is an experimental regime not previously explored in a transport experiment. However, it is possible that the lack of resolution of the LLs energies well below E_F may be an effect of the quasiparticle lifetime, τ_{qp}, which we expect [10] to

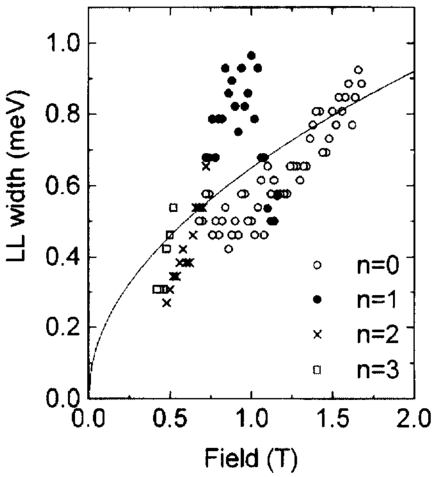

Fig. 5. Landau level widths versus magnetic field for the first four levels. The fitted curve shows the $B^{1/2}$ dependence.

vary as $(E_F\text{-}E)^2$. When $\omega_c\tau_{qp} < 1$, the Landau model will break down.

Fig. 5 shows the full-width, half-maximum of the $n = 0$, 1, 2, and 3 LLs versus magnetic field. Note that we only consider LLs below E_F. In a model using short-range scattering, Ando and Uemura [11] proposed a relationship $\Delta E_{LL} \approx aB^{1/2}$, where ΔE_{LL} is the LL width, and α is a constant. Included in Fig. 5 is a $B^{1/2}$ fit to all the data, from which we obtain a value for α of 0.65 meV $T^{-1/2}$, which corresponds to a mobility of $\sim 48\,000\ \text{cm}^2/\text{Vs}$. However, the results are more consistent with a linear dependence with a slope of 0.6 meV/T. Previous measurements have indicated either the LL width increasing with B [12,13] or remaining constant [14]. In our case, we stress that we measure the local width of a LL which may be different to that averaged over a large area. It can be seen in Fig. 4 that the $n = 0$ LL width is consistently less than other LL widths at the same field. The reason for this is not clear, although we have some evidence (not shown) that it may reflect a difference in the effective Landé g-factors for the LLs.

In summary, we have used tunnelling through a single-quantum dot as a unique spectroscopic probe of a 2DEG in a magnetic field. In addition, we study the many-body enhancement of the tunnel current when the Fermi edge of the 2DEG matches the energy level of the dot.

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