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Fermi edge singularities in high magnetic fields

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

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

Abstract

The current voltage characteristics of a single barrier tunnelling device which contains self-organized InAs quantum dots within the barrier are studied in zero and strong magnetic field conditions (both perpendicular and parallel to the interfaces). It is observed that in all cases there are large peaks whenever the energy of the bound state of a dot approaches the chemical potential of the 2d electron system formed at an interface. These are identified as thermally broadened Fermi-edge singularities which arise from many-body contributions to the tunnelling amplitude. We note that the standard theory of such singularities appears to work well in situations when the spin states of the dot are Zeeman split but is qualitatively incorrect in zero field. In the quantum Hall regime the peak height is an oscillatory function of magnetic field in agreement with theoretical predictions.

Keywords: Quantum Hall effect; Fermi edge singularities; Tunnelling

1. Introduction

Resonant tunnelling via two dimensional bound states in double barrier heterostructures has been very well studied. There is now considerable interest in systems in which tunnelling occurs via zero dimensional states located within a single barrier. These zero dimensional states can either be bound to impurity clusters [1] or nanoscale quantum dots [2]. In this report we will describe the results of our investigations of the properties of such a system formed by depositing a self-organized array of InAs quantum dots within an AlGaAs barrier. The application of an external bias voltage to the device leads to the formation of a 2d electron system (2des) on one side of the barrier. At low bias voltages the current flow from the 2des is almost entirely due to tunnelling via a single quantum dot which has its bound state energy resonant with the lowest sub-band of the 2des. Fine tuning of the bias allows the energy of the dot state to be moved with respect to the levels of the 2des. The detailed experimental geometry of our system is described in [3]. The energy of the zero dimensional state bound to the dot is related to the applied bias voltage, V, by

$$E_{\rm d}(V) = E_{\rm d}(0) - efV,$$

where f is an electrostatic 'leverage factor' which is typically of the order of 0.1 in the samples studied. Naively, one would expect that a plot of the tunnelling current against bias voltage would provide a map of the local density of states [4] of the 2des at the site of the dot. In fact, what is observed is even more interesting because of the presence of 'final state interactions' resulting from the change

* Corresponding author. Tel.: +44 115 951 5145; 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.

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in the charge state of the dot after a tunnelling event has occurred. These interactions give rise to Fermi-edge singularities analogous to those seen in X-ray absorption experiments [5] in metallic systems.

2. Fermi edge effects in zero magnetic field

In the absence of an applied magnetic field, the tunnelling characteristics (see Fig. 1(a)) are superficially similar to those predicted using the standard theory of the Fermi-edge singularity [5] adapted to the 2d to 0d tunnelling situation [6]. The data show a strong peak at the threshold voltage followed by a roughly constant lower current at higher voltage which eventually drops to zero when the dot energy is pulled below the bottom of the 2d sub-band. The temperature dependence of the shape of the peak is qualitatively what would be expected for a Fermi-edge singularity. In detail, however, there are some curious anomalies. Firstly, the position of the current peak is temperature independent whereas the standard theory would predict that it should move to lower energy (higher voltage) with increasing temperature. This behaviour differs from the impurity systems [1] studied previously which show the expected temperature dependence. The second anomaly can be seen from Fig. 1(b) where the current integrated over bias voltages from zero up to some value V,

$$P(V) = \int_0^V \mathscr{I}(V')\,\mathrm{d}V',$$

is plotted against V. This quantity increases monotonically with V but eventually becomes a constant (although this is not visible on the graph). A simple sum rule [7], which only assumes that the electron tunnels from the 2des to an empty, featureless dot, relates the asymptotic value of this quantity to the local electronic density, ρ, by

$$\lim_{V\to\infty} P(V) = \frac{2\pi}{ef\hbar} w^2 \rho(r_\mathrm{d}),$$

where w is the bare tunnelling matrix element and r_d is the position of the dot in the plane. Experimentally we know from the constancy of the onset voltage that the local charge density has negligible temperature dependence but Fig. 1(b) clearly shows that the left hand side of this sum rule decreases significantly with increasing temperature. These two anomalies probably have a common origin: it can be seen from Fig. 1(b) that the extra contribution to P at low temperatures comes from the peak close to the Fermi edge as the graphs of P run parallel once V is above the threshold region.

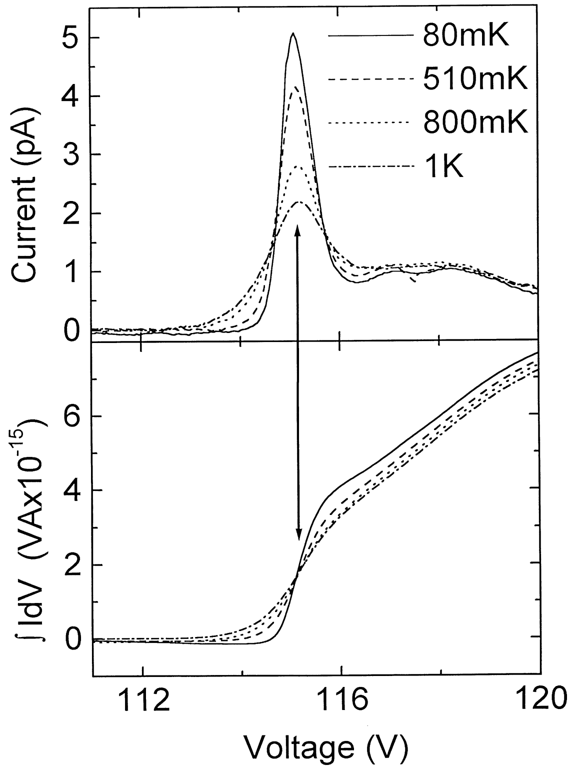

Fig. 1. (a) A plot of tunnel current against bias voltage in zero magnetic field for temperatures in the range 80 mK to 1 K. (b) A plot of the integrated tunnel current $P(V)$ against bias voltage V for the same temperatures as in 1(a).

3. Tunnelling in parallel magnetic field

When a magnetic field is applied in the plane of the 2des, it has no effect on the orbital motion of the 2d electrons but it does cause a Zeeman splitting of the two spin states in both the dot and the 2des. Fig. 2 shows a plot of the I–V characteristics of a device subject to an in-plane field of 5.8 T

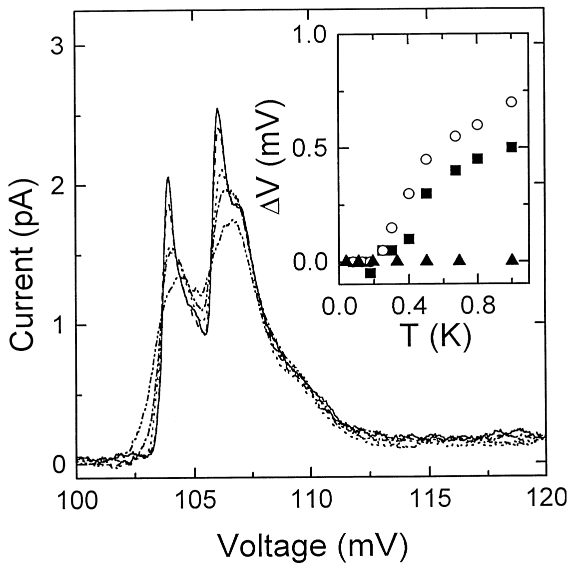

Fig. 2. Plots of the tunnel current against bias voltage in the presence of an in-plane field of 5.8 T. The plots are for temperatures 80, 130, 300, 400 and 670 mK. The inset shows the temperature dependence of the peak height for the two spin split peaks in this case (□ and ○). The temperature dependence of the peak position in the zero field case is shown (△) for comparison.

over a range of temperatures between 80 and 670 mK. The onset peak has clearly split into two: each peak corresponding to one of the spin states of the dot being coincident with the chemical potential of the 2des. These results allow the Landé g-factor of the dot to be extracted [8]. The value obtained from this analysis, 0.89, is very different from the bulk value for InAs (−14.8) but when the effects of size quantization and strain are taken into account this value is not unreasonable. The inset to Fig. 2 shows the temperature dependence of the peak position: the open circles and the squares show the positions of the two peaks in question while the triangles show the temperature dependence of the peak in zero field for comparison. It can be seen that the two spin-resolved peaks behave in the manner that would be expected for thermally broadened Fermi-edge singularities: it is the spin degenerate case that is anomalous. It is therefore tempting to suppose that the anomaly is related to the spin degree of freedom and that the peak in this case is due to Kondo-like behaviour associated with final state interactions between the 2des and the localized spin on the charged dot.

4. Quantum Hall regime

When a magnetic field is applied to the device perpendicular to the 2des, the electronic states become Landau quantized. Varying the bias voltage allows the dot energy to be swept through the occupied Landau bands. On fairly general grounds [7] one expects that close to the onset threshold the current will display a power law divergence at $T = 0$ of the form

$$\mathscr{I}(V) \sim |V - V_{\text{th}}|^{-ug(\mu, r_{\text{d}})},$$

where $g(\mu, r_{\text{d}})$ is the local density of states at the chemical potential at the site of the dot and u is a scale for the strength of the interaction between the charged dot and the 2des. At finite temperatures this divergence will be rounded to a peak whose height will depend on the magnitude of the local density of states. This is born out by the results shown in the lower trace of Fig. 3 (which are typical of results obtained on several devices) which show strong oscillations of the onset peak

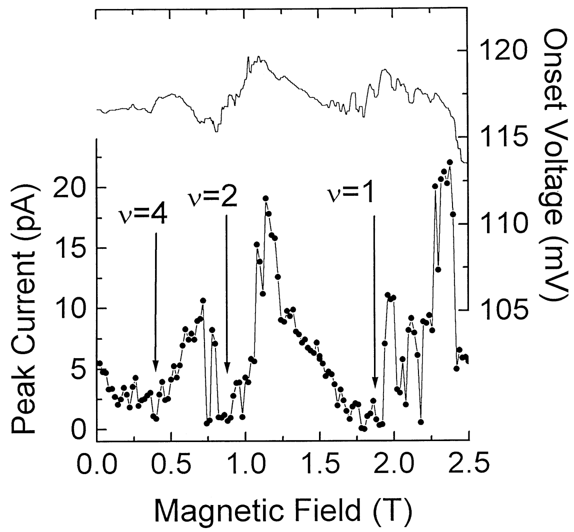

Fig. 3. Plots of peak current and onset voltage (defined as the voltage above which the current first exceeds an arbitrary value) as a function of perpendicular magnetic field. The labels indicate the Landau level occupancies at various fields.

height as the magnetic field (and hence the position of the chemical potential within a Landau band) is varied: indeed the tunnelling is all but suppressed when the chemical potential lies between Landau bands. The upper trace shows the variation in the threshold voltage with field which partly reflects the usual oscillations in the chemical potential position with field but also probably has contributions from the final state interaction effects.

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