Landau-Level Spectroscopy of a Two-Dimensional Electron System by Tunneling through a Quantum Dot

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(Received 20 January 1997; revised manuscript received 19 August 1999)

A single InAs self-assembled quantum dot is incorporated in the barrier of a tunnel diode and used as a spectroscopic probe of an adjacent two-dimensional electron system from the Fermi energy to the subband edge. We obtain quantitative information about the energy dependence of the quasiparticle lifetime. For magnetic field B, applied parallel to the current, we observe peaks in the current-voltage characteristics $I(V)$ corresponding to the formation of Landau levels. Close to filling factor $\nu = 1$ we observe directly the exchange enhancement of the Landé g factor.

PACS numbers: 73.40.Gk, 71.70.Di, 73.20.Dx, 85.30.Vw

The highly degenerate eigenstates of the single-particle Hamiltonian for electrons in a magnetic field B, known as Landau levels (LLs), provide the basis for the understanding of many of the electronic properties of two-dimensional conductors. As B is increased, so is the energy and degeneracy of each level, leading to a modulation of the density of states at the Fermi energy E_F, and a variety of readily observable effects [1]. For example, Shubnikov–de Haas oscillations appear in the linear conductivity. These experiments, however, do not provide information about the LLs below the Fermi energy. It is possible to obtain information about the lower energy states, for example from luminescence studies [2], but in such measurements the energy resolution is limited by spatial inhomogeneities in the optical transition energies. To date, transport experiments [3–5] that investigate tunneling of electrons with energies less than E_F have not provided clear resolution of the LL density of states.

In this Letter, we perform tunneling spectroscopy on a two-dimensional electron system (2DES) by measuring the tunnel current from a 2DES through the zero-dimensional (0D) ground state of a single quantum dot embedded in the barrier of a tunnel diode. The linewidth of the state is less than 10 μeV, which determines the resolution of the probe. We observe clearly the formation of the LL and their development with increasing B. Although experiments have been performed on similar systems [6–8], none have reported the unambiguous observation of LL. The LL appear successively as B is increased, which we interpret in terms of an energy-dependent quasiparticle lifetime, τ_{qp}. At higher B, where the filling factor $\nu = nh/eB = 1$ (n is the areal density of electrons), we observe directly the exchange enhancement of the Landé g factor which occurs at these filling factors. At filling factors just below $\nu = 1$ and $\nu = 2$, the current-voltage characteristics $I(V)$ exhibit a series of additional sharp peaks.

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 in the Stranski-Krastonov mode on the center plane of the barrier, producing a dot density of $\sim 2 \times 10^{15}$ m^{-2} with a typical size $\sim$10 nm. A detailed description of the devices can be found in Ref. [6]. When a bias is applied across the device, a 2DES forms in an accumulation layer on one side of the AlAs barrier (see Fig. 1). 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 tunnel through the dot into the collector and a current flows. Therefore, as we adjust the voltage we expect to see a step change in the current, limited only by kT smearing, 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 density.

Typical low-temperature $I(V)$ curves near the current onset for a 5 μm diameter mesa are shown in Fig. 2(a). We define forward bias as the direction in which the electrons tunnel through the thicker part of AlAs barrier before entering the dot (see Fig. 1). The barrier on the other side of the dot is thinner due to the finite height of the dot,

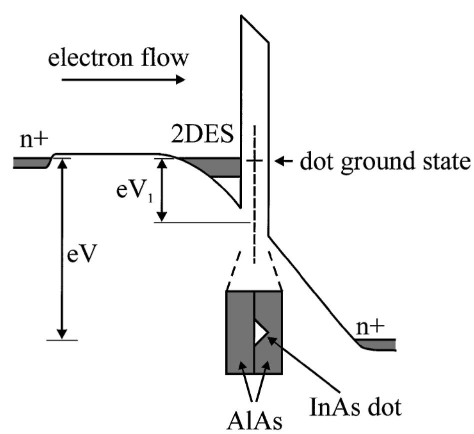

FIG. 1. Conduction band diagram of the experimental device under bias. The electrostatic leverage factor is $f = dV/dV_1$. The expanded inset shows the geometry of the dot within the barrier.

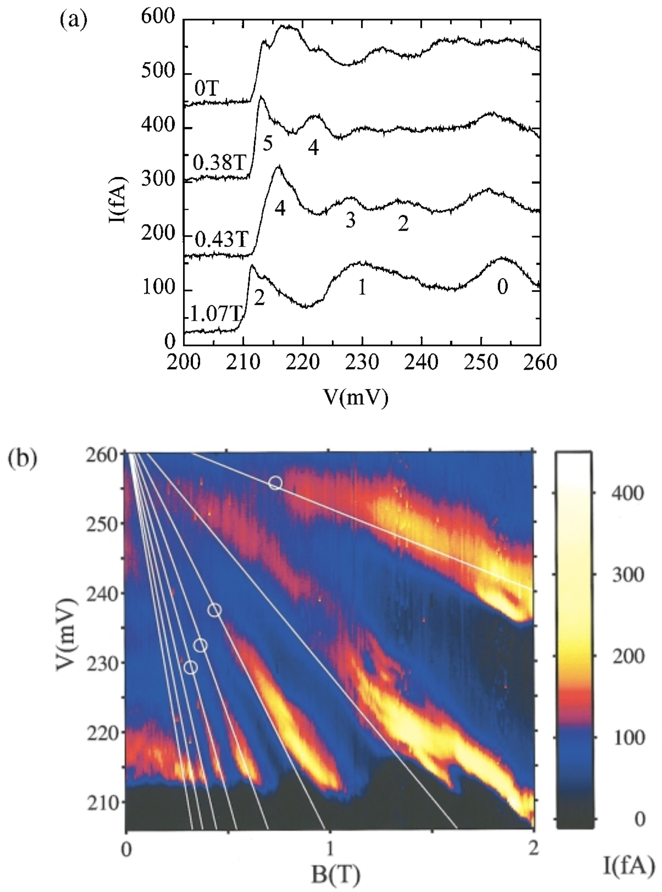

FIG. 2. (a) $I(V)$ in forward bias at 0.3 K in four magnetic fields. Peaks are labeled according to the corresponding LL index. Curves are offset for clarity. (b) (color) Color-scale plot of I vs V and B. The lines are the expected energies of LLs. The circles represent the points where the peak due to a particular LL can be just resolved.

so in forward bias the current is determined by the rate at which the electrons tunnel into the dot and the mean charge on the dot is much less than e. The thermal activation of the current onset indicates that the feature in Fig. 2(a) is due to tunneling through a sharply defined state of a single dot. Additional evidence is provided by the existence of Coulomb blockade steps in reverse bias [6]. Although there are ~40 000 dots in the device, most have their electron ground state energies well above the GaAs conduction band edge, and hence above the Fermi energy of the 2DES at zero bias. The dots that we observe are at the lower energy edge of the distribution [9]. In the $B = 0$ curve of Fig. 2(a), the QD is resonant with the Fermi energy of the 2DES at 210 mV and the subband edge at 265 mV, corresponding to a Fermi energy of 3.8 meV after taking into account the electrostatic leverage factor $f = 14$ (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 we are able to scan the complete distribution of filled states with a single level which is analogous to the narrow slit of a spectrometer.

The peak in $I(V)$ at the current onset in Fig. 2(a) is a Fermi edge singularity (FES), previously observed in tunneling from a 2DES through an impurity state in a quantum well [5]. The detailed behavior of the FES in a magnetic field will be discussed elsewhere; in this paper, we concentrate principally on the current at voltages beyond the FES where we expect that the current is largely determined by the local density of states in the 2DES [4] close to the dot. 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. The localized character of the dot state means that the tunnel current is very insensitive to the electron k vector, and we may assume that the tunneling probability is not dependent on energy [10] provided a suitable state is available for tunneling.

Figure 2(a) shows $I(V)$ at various B applied parallel to the current. For this device, below 0.3 T we do not observe any evidence for Landau quantization in $I(V)$. However, the 0.38 T curve shows two clear peaks which we associate with the $N = 4$ and 5 LL, where the LL energies are given by $E_N = (N + 1/2)\hbar\omega_c$. The identification of the index N is justified by the fan diagram discussed below, but we note that the $N = 3$ peak is barely visible at 0.38 T and that no LL with lower value of N may be resolved at this field value. Nevertheless, the appearance of LLs close to E_F for B between 0.25 and 0.3 T would correspond to a 2DES mobility around 3.5–4 $m^2\ V^{-1}\ s^{-1}$. As B is increased, Fig. 2(a) shows the successive emergence of lower energy LLs. At 0.43 T, we are able to resolve down to $N = 2$. There is also a broad peak around 255 mV. Eventually, the $N = 0$ and 1 LLs emerge from this peak, but below 0.4 T its bias position does not depend strongly on B. The $N = 0$ and 1 LL are clearly resolved in the curve for 1.07 T.

Figure 2(b) shows a color-scale plot of current as a function of V and B below 2 T. Note that as each LL increases its energy with increasing B, the corresponding peak moves to lower voltage. The values of $(N + 1/2)\hbar\omega_c$ are drawn as solid lines with no adjustable parameters, using the measured leverage factor $f = 14$, obtained from the thermal activation of the current onset, and an effective mass, $m^*/m = 0.070$. This plot confirms the identification of the peaks in $I(V)$ with LLs. The weak structure in $I(V)$ at $B = 0$ has been attributed to mesoscopic variations in the density of states due to quantum interference [4]. Certainly, there is no general progression from this structure to the peaks associated with the LL. However, the broad peak around 255 mV at low B [see Fig. 2(a) at 0.38 T and Fig. 2(b)] does merge with the peaks due to the $N = 0$ and 1 LLs; we have no firm explanation for the origin of this peak. Note also the oscillatory behavior of the current onset in Fig. 2(b), reflecting the variation in the chemical potential due to the successive depopulation of the LLs with increasing B. This enables us to calculate n; we find $n = 1.2(\pm 0.1) \times 10^{15}\ m^{-2}$ for

$V \approx 210$ mV, corresponding to $E_F = 4$ meV, consistent with the estimate above from the $I(V)$ curve at low B.

We interpret the successive emergence of LLs of decreasing order as a consequence of the quasiparticle lifetime τ_{qp}, which we expect to become shorter as $|E_F - E|$ increases. At a particular B, we assume $\omega_c \tau_{\mathrm{qp}} > 1$ in order to resolve a LL. Hence, there is a critical value of $|E_F - E|$ above which no LL can be resolved. Alternatively, at a particular energy, there is a corresponding critical value of B. Experimentally, we define the critical field for a particular LL as the value of B at which we are just able to resolve a given LL peak in $I(V)$. These points are shown as circles in Fig. 2(b) for $N = 0$, 2, 3, and 4. Since both $N = 0$ and 1 emerge from the broad peak, we select the point where the $N = 0$ peak is independently resolved. The value of $|E_F - E|$ is determined from the voltage axis and the leverage factor. In Fig. 3 we plot the critical values of τ_{qp}^{-1} (assuming $\omega_c \tau_{\mathrm{qp}} \sim 1$ at the critical B) against $(E_F - E)$ for $N = 1$ to 4. The data form a good straight line through the origin and are consistent with $\tau_{\mathrm{qp}} = \beta\hbar/(E_F - E)$, with $\beta = 2.5$. This behavior is not consistent with the expected variation for a conventional Fermi liquid [11] $\tau_{\mathrm{qp}} \sim (E_F - E)^{-2}$, but is in quantitative agreement with the predictions of Varma *et al.* [12] for a marginal Fermi liquid. However, Hawrylak *et al.* [13] have pointed out that the predicted behavior for the conventional Fermi liquid should only be observed very close to E_F. We are not aware of any other experiments which provide direct evidence for the variation of the quasiparticle lifetime with energy so far below E_F.

At about 5 T, the chemical potential enters the energy gap between the two spin-split components of the lowest LL, $\nu = 1$. However, the interpretation of the $I(V)$ curves is complicated by the nonlinear character of the tunnel diodes. Because the single barrier device is essentially a capacitor, the density of the 2DES in the accumulation layer increases with increasing V. Although the variation of n is relatively small in the voltage range of interest, $I(V)$ curves at constant B do not correspond precisely to constant ν. To correct for the variation of n, we measured a series of $I(V)$ characteristics at 10 mT intervals in the vicinity of $\nu = 1$. The depopulation of the higher energy, spin-polarized LL gives a precise value of B for $\nu = 1$ and hence the value of n at this voltage. Assuming a linear variation of n with V, we are then able to determine n, and hence ν, for each of the data points in the $I(V)$ curves. Figure 4 shows a grey scale plot of the current with axes of voltage and inverse filling factor. The diagonal streaks represent lines of constant B in the original data.

There are two striking features seen in Fig. 4 at $\nu = 1$. First, the onset to tunneling through the lower-energy, spin-polarized LL shifts abruptly from 0.213 V just above $\nu = 1$ to 0.229 V just below. This corresponds to a shift of the LL to *lower* energy, in sharp contrast to the monotonic increase in energy of the peaks corresponding to the other LL as B increases [Fig. 2(b)]. The shift of this LL to lower energy is a direct observation of the exchange enhancement [14] of the spin splitting which is known to occur near $\nu = 1$. Our observation indicates that the spin gap changes abruptly at $\nu = 1$ so that, strictly, one should not interpret it in terms of an effective Landé g factor, g^*. However, since this representation is so common in the literature, we use our data to extract comparable values. From the decrease in energy of the lower spin-polarized LL at $\nu = 1$, relative to the measured spin gap just above $\nu = 1$, we are able to estimate that g^* increases to 9 ± 1 just below $\nu = 1$ from a nonenhanced value of 2 ± 1. The values include a small correction for the spin splitting of the dot ground state [15]. These values are in reasonable agreement with those of Dolgopolov *et al.* [16] who measured $g^* = 7$ at $\nu = 1$ using a capacitance technique which did not allow them to see the variation of g^* with B.

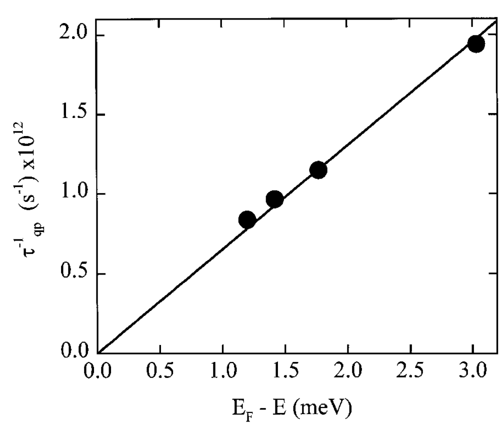

FIG. 3. Values of τ_{qp}^{-1} vs $(E_F - E)$. The line is $\tau_{\mathrm{qp}}^{-1} = (E_F - E)/\beta\hbar$ with $\beta = 2.5$.

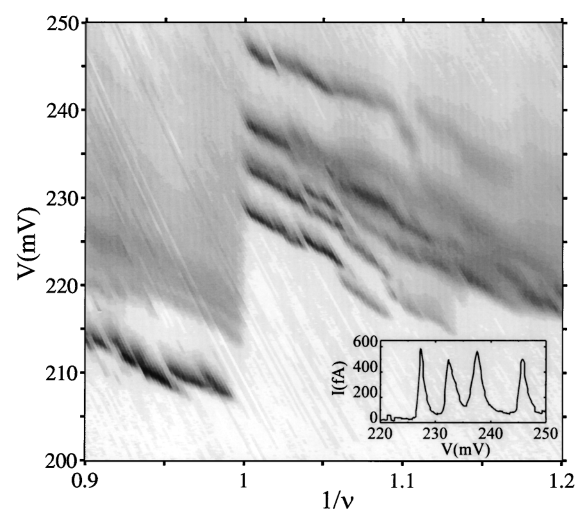

FIG. 4. Grey-scale plot of current vs voltage and inverse filling factor in the vicinity of $\nu = 1$. Inset: $I(V)$ at constant $\nu^{-1} = 1.01$.

The second feature at $\nu = 1$ is the onset of a multiple peak structure in the lowest spin-polarized LL. The four peaks in $I(V)$ appear simultaneously at $\nu = 1$; there are three evenly spaced ($\sim$360 μeV) peaks and a fourth about 570 μeV higher in energy. We have seen a similar structure in other devices at $\nu = 1$, although with lower n so it is not so well defined. We also observe very similar peaks in this device just below $\nu = 2$ with good resolution, and with poorer resolution at $\nu = 4$. In each case, the peaks do not appear until the chemical potential has entered the lower energy Laudau level. The origin of the peaks is not clear. Since they appear near integer filling factors, they must be associated with the emitter 2DEG and not the dot. This rules out Coulomb blockade in the dot as a possible explanation. One possibility is that the tunneling occurs from a finite-size pool of $\sim$4–5 electrons in the emitter, possibly formed by the disorder induced by the strain field of the dots [9]. The peaks would then reflect the splitting in the Landau states due to this potential. Consistent with this picture, the peaks depopulate with increasing B (see Fig. 4). Although this is an attractive explanation, there are problems. First, the sharpness of the peaks is much more pronounced than has been observed previously in tunneling through localized states [17,18] [see inset to Fig. 4 for an $I(V)$ plot]. Also, the peak structure becomes visible only when the chemical potential enters the LL. Second, whereas at most values of B, the temperature dependence of $I(V)$ is confined to within kT of E_F, in this regime the four peaks, which are up to 100 kT below E_F, are strongly affected by temperature; they are still visible at 1 K but are almost completely quenched at 2 K $\ll E_F/k$. The latter observation suggests that interaction effects are important. Shahbazyan and Ulloa [19] have recently predicted the existence of sub-LL structure in the presence of resonant scattering but their model is not applicable to our system where we have only one state resonant with the 2DES during the measurement.

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 formation of Landau levels and the exchange enhancement of the spin splitting when $\nu = 1$. We are able to study quantitatively the quasiparticle lifetime below E_F. We also observe additional sharp peaks in $I(V)$ when the chemical potential lies just inside a Landau level.

This work and one of use (L. E.) are supported by the Engineering and Physical Science Research Council (U.K.). We are grateful to Boris Muzykantstkii for helpful discussions.

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