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Tunnelling between two-dimensional electron gases up to 25 T

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Abstract

We have measured the tunnelling between 2 two-dimensional electron gases at magnetic fields B up to 25 T. When the carrier densities of the two electron layers are matched and for filling factors $\nu < 1$, we observe a clear gap in the differential conductance dI/dV as a function of the voltage V_{sd} applied between the layers. We have measured tunnelling peak positions and fitted gap parameters Δ that are proportional to B and do not depend on the carrier concentration of the two layers. These results suggest that we are observing a gap that is different in origin to that proposed by current theories.

Following recent experimental work [1–3] there has been much theoretical interest in the tunnelling of electrons out of a two-dimensional electron gas (2DEG) in a strong magnetic field [4–9]. Following on from experiments of Demmerle et al. [2], Eisenstein et al. [3, 10] measured the tunnelling from one 2DEG to a similar parallel 2DEG, the two being separated by a 175 Å barrier. In zero magnetic field there is resonant tunnelling between the two 2DEGs when their carrier densities are equal. In a strong magnetic field however, the current–voltage (I–V) characteristics between the two layers exhibit a gap when the filling factor ν is less than unity. This suppression of tunnelling has been interpreted as evidence for electron–electron interactions within a 2DEG, and the resulting gap was labeled a "Coulomb gap". It was also suggested [3] that, at high magnetic fields, electron–electron interactions are responsible for lowering the effective mass of electrons in the lowest Landau level (LL).

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In this paper we extend earlier investigations [11] of the gap of a double 2DEG to magnetic fields up to 25 T. We observe a gap in the tunnelling characteristics, but we shall show that the gap and the associated tunnelling peak do not follow the $\sqrt{B}$ behavior predicted by current theories. Instead we observe a gap and a tunnelling peak that are both linear in B.

Double quantum wells and buried patterned back gates were fabricated by *in situ* ion beam lithography and molecular beam epitaxy regrowth. These techniques allow patterned back gates to be grown into the wafer structure, the details of which have been published elsewhere [12–14]. Subsequent optical lithography was used to define a Hall bar mesa, and to deposit Au Schottky gates aligned with the back gates. The device was put into the tunnelling configuration by applying negative voltages to side front and back gates. The two electron gases then overlap in a 100 μm × 150 μm area. The carrier densities of the top (n_1) and bottom (n_2) 2DEGs in the tunnelling area were controlled by voltages applied to the top (V_{g1}) and bottom (V_{g2}) gates, respectively.

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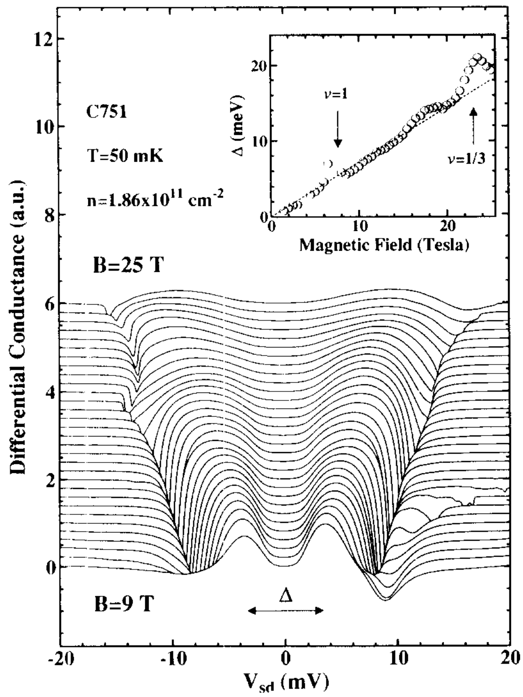

Fig. 1. Main figure: low temperature dI/dV versus V_{sd} characteristics when $n_1 = n_2 = 1.86 \times 10^{11}\ cm^{-2}$ between 9 and 25 T, measured at 0.5 T intervals. Successive sweeps are vertically offset. The gap Δ can be directly measured from the peak-to-peak positions in dI/dV. Inset: the measured gap Δ from 2–15 T; the dotted line shows the fit $\Delta = 0.43\hbar\omega_c$.

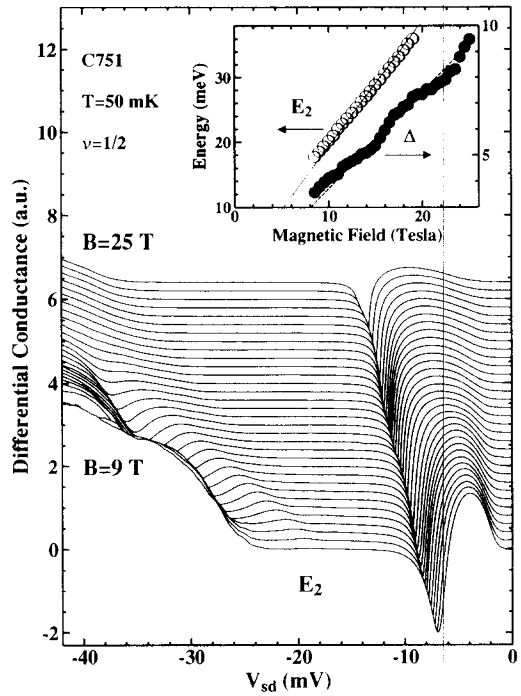

Fig. 2. Main figure: differential conductance dI/dV versus V_{sd} at $\nu = \frac{1}{2}$ from $B = 9$–25 T, measured at 0.5 T intervals. Successive sweeps are vertically offset. Inset: the measured tunnelling energy E_2 and the gap parameter Δ with fits $E_2 = 1.16\hbar\omega_c$ and $\Delta = 0.44\hbar\omega_c$.

In contrast to our previous study [11], we measure the differential conductance dI/dV as a function of the voltage V_{sd} applied between the two 2DEGs. The sample was cooled in a dilution fridge and high magnetic fields were provided by the hybrid magnet. Fig. 1 shows vertically offset sweeps of the differential conductance dI/dV versus V_{sd} measured when $n_1 = n_2 = 1.86 \times 10^{11}\ cm^{-2}$ from $B = 9$–25 T. Around zero bias the conductance is suppressed and then showed a maximum and then a NDR region as the voltage V_{sd} is increased. In previous studies [10, 11] the I–V sweeps have been successfully fitted to the form $I = I_0 \exp(-\Delta/V)$ over a large voltage range. Mathematically the peak-to-peak distance across zero bias (see Fig. 1) of dI/dV is equal to Δ, and in the inset to Fig. 1 we have plotted Δ as a function of the magnetic field B. Except for the peaked structure near the quantum Hall states at filling factors $\nu = \frac{1}{3}$ and $\nu = 1$, the gap Δ follows the straight line fit $\Delta = 0.43\hbar\omega_c$. The differential measurements contain the same information as the DC I–V sweeps, except that the tunnelling peak that was observed at $0.3\hbar\omega_c$ in the I–V sweeps is seen as a peak at $\Delta/2 \approx 0.2\hbar\omega_c$ in dI/dV.

By tuning n_1 and n_2 with the top and bottom gates we can adjust the filling factor in the two 2DEGs in a magnetic field to any desired value; Fig. 2 shows the differential conductance measured at $\nu = \frac{1}{2}$ from $B = 9$–25 T. At the lowest magnetic field ($B = 9\ T$) there is a conductance peak at 20 mV; as the magnetic field was increased this structure moved linearly to higher magnetic field. This peak (labelled E_2) is an inter LL transition that was first observed by Demmerle et al. [2] The inset of Fig. 2 shows the E_2 peak position and the value of Δ as a function of magnetic field B. The two data sets can be fit by the functional forms $E_2 = 1.16\hbar\omega_c$ and $\Delta = 0.44\hbar\omega_c$, where $\hbar\omega_c = 1.67$ meV/T for GaAs. In previous studies [11] the E_2 peak was fit to the form $E_2 = 1.3\hbar\omega_c$, in this particular case the lower value of 1.16 is obtained because we are measuring a peak in the differential conductance dI/dV rather than in the DC current I.

Fig. 3 shows sweeps of dI/dV versus V_{sd} when $n_2 = 3.3 \times {}^{11}\ cm^{-2}$ and $B \sim 16$ T. The E_2 tunnelling peak at 35 mV ($\approx 1.2\hbar\omega_c$ at 16 T) was invariant as the top 2DEG carrier concentration n_1 was varied from 3.3 to

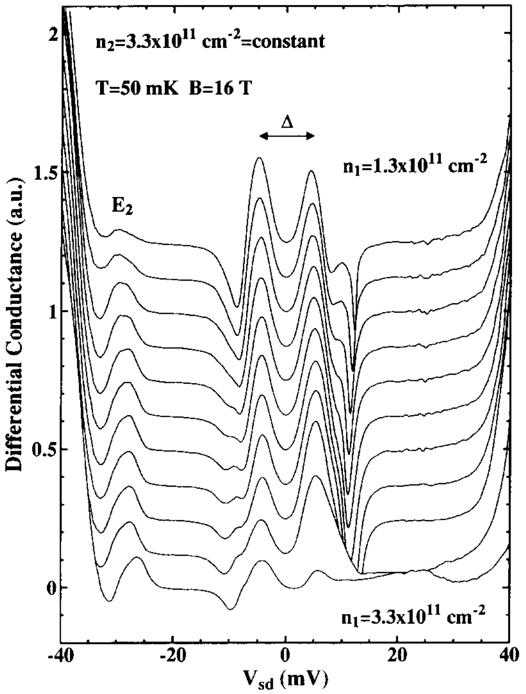

Fig. 3. The differential conductance dI/dV versus V_{sd} measured at $n_2 = 3.3 \times 10^{11}$ cm^{-2} and $B = 16$ T, as n_1 was varied from 3.3 to 1.3×10^{11} cm^{-2} in ten equal steps. Successive sweeps are vertically offset.

1.3×10^{11} cm^{-2} in ten equal steps. Likewise the structure at 6 mV, from which we derive the value Δ, remained fixed as n_1 was varied.

Theoretical descriptions of the gap and the first tunnelling peak can be subdivided into those that ignore interlayer correlations [4–7] and those that incorporate interlayer interactions [8, 9]. Quantum mechanical calculations [5,6] of the former type predict that, for the compressible state at $\nu = \frac{1}{2}$, the gap should scale with the energy $e^2/\varepsilon l_B \sim \sqrt{B}$. A classical model [8] of this system predicts that, for fixed carrier densities $n_1 = n_2$, the gap Δ is linear in ν for $0.3 < \nu < 0.9$. Our data in Fig. 1 shows that both of these theories are not an accurate description of the system; over a large magnetic field range we are able to fit Δ to a linear function of B, rather than being proportional to $\sqrt{B}$ or $1/B$.

In a classical theory [8] of the gap it has been suggested that the electrons in one layer anti-correlate with the electrons in the other layer. This situation is readily visualized when the carrier concentrations are equal, however it is hard to imagine such anti-correlations existing over the large mismatch of carrier concentrations that we have measured in Fig. 3.

In conclusions, with the benefit of our high field measurements we can confirm that the gap only depends on the magnetic field B, and does not depend on the filling factor ν.

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