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Size-effects and tuning of phase coherence in a double quantum well mesoscopic wire

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Abstract

We have investigated the magnetoresistance properties of mesoscopic wires fabricated from a modulation-doped GaAs/(AlGa)As double quantum well structure containing two coupled 2D electron gases (2DEGs). An in-plane magnetic field, B, "tunes" the tunnelling between the 2DEGs and, in a Hall bar device, leads to a resistance feature at $B \approx 10$ T due to a van Hove singularity in the density of states. In mesoscopic wires this feature becomes a strong resistance peak. We attribute this enhancement to a size effect. In addition, we observe universal conductance fluctuations with the in-plane B. These disappear when B is strong enough to suppress the tunnelling between the wells.

Keywords: Double quantum wells; Mesoscopic systems; Phase coherent; Universal conductance fluctuations

Tunnelling between coupled two-dimensional systems (2DESs) in a magnetic field, B, has attracted a great deal of recent interest with B applied either perpendicular [1] or parallel [2] to the plane of the 2DESs. The latter case is attractive because it allows tuning of the interwell tunnelling as a result of the shift in momentum introduced by B. This gives rise to two types of modification of the magnetoresistance of the parallel 2D systems. The first type is a result of the different mobilities in the two quantum wells. Where there is strong tunnelling between the wells, the higher scattering rate is important but when tunnelling is suppressed, the current is carried by the higher mobility well. In a balanced system a negative magnetoresistance is observed [3,4] for an in-plane B. The second type of effect occurs at the point when the in-plane field is almost sufficient to switch off completely the tunnelling between the wells; i.e. the shift in momentum is larger than $2\hbar k_F$, the diameter of the Fermi circle in either well. The symmetric–antisymmetric splitting of the energy dispersion curve leads to a van Hove singularity in the density of states and a feature in the longitudinal resistance [5,6].

In this paper we report measurements on a coupled quantum well system which has been fabricated into mesoscopic wires of width smaller than the elastic mean free path and comparable to

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the phase-coherence length. We study the longitudinal transport of the wires with B applied perpendicular to and in the plane of the wells; in the latter case B may be either parallel or perpendicular to the axis of the wire. For comparison, we also study macroscopic Hall bars fabricated from the same material. There are two principal differences between the behaviour of the wires and the Hall bar. First, in the wires, when B is applied in-plane and perpendicular to the axis, there is an enhancement of the magnetoresistance feature due to the van Hove singularity. Second, we observe universal conductance fluctuations (UCF) in the wires of magnitude $\sim e^2/h$ when B is applied in any direction, including when B is in the plane of the quantum wells.

The double-quantum well layer was grown by molecular beam epitaxy and comprises two 14.4 nm GaAs quantum wells separated by a 2.5 nm $(Al_{0.33}Ga_{0.67})As$ barrier. Two 41 nm Si doping layers ($n = 1.33 \times 10^{18}\,m^{-3}$ and $n = 1.33 \times 10^{17}\,m^{-3}$) are situated symmetrically, each with a 41 nm $(Al_{0.33}Ga_{0.67})As$ spacer from the top and bottom quantum wells, respectively.

To characterise the wafer, we fabricated a macroscopic Hall bar with a surface metallic gate and performed magnetotransport measurements using a conventional 4-wire AC technique. With B perpendicular to the plane of the wells (hereafter denoted B_n), the Shubnikov–de Haas oscillations (SdHO) show a total electron density of $4.3 \times 10^{15}\,m^{-2}$ in the wells. The wells are balanced when the applied gate voltage is very close to zero, $V_g = 40\,mV$. In balance the symmetric and antisymmetric states have occupations of $2.5 \times 10^{15}\,m^{-2}$ and $1.8 \times 10^{15}\,m^{-2}$ respectively, indicating a symmetric–antisymmetric splitting of $\Delta = 2.6\,meV$, consistent with that observed in other similar devices [3,4,6]. We estimate the mobilities of the two wells to be 47 and $126\,m^2\,V^{-1}\,s^{-1}$ based on the low-field magnetoresistance [7].

Fig. 1 shows the magnetoresistance of the Hall bar at 0.3 K for an in-plane B applied parallel (denoted $B_{\|}$), and perpendicular (denoted $B_{\perp}$), to the current for zero gate voltage. The data are very similar to those shown in Ref. [6] for a very similar device. The resistance resonance (RR) around zero field [3,4,8] and the resistance feature (RF) around

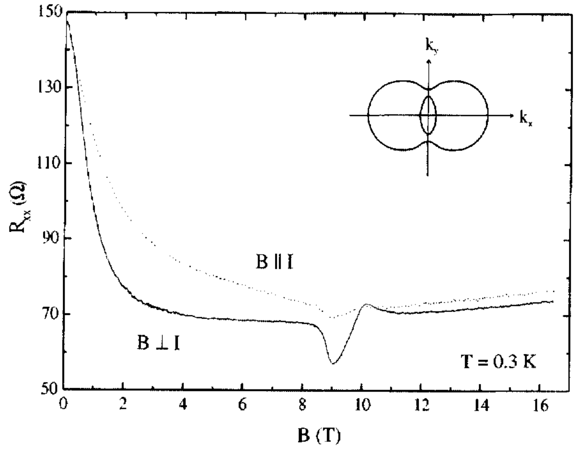

Fig. 1. In-plane magnetoresistance of the Hall bar sample. Solid line is $B_{\perp}I$, dotted line is $B_{\|}I$. Inset: Fermi contour with in-plane $B_{\|}y$.

11 T [6] have been observed previously. In broad terms, the RR is a result of the delocalisation of electrons between the two quantum wells. Since the wells have different mobilities, at $B = 0$, the effective scattering rate is the average between the two quantum wells. The in-plane field acts to suppress the tunnelling [2]. The RF is more subtle and is a result of a distortion of the energy dispersion curve by the symmetric–antisymmetric splitting. It occurs when the shift in the k-vector of the states in one well relative to the other, $\Delta k = eBd/\hbar$, corresponds to the Fermi diameter, $2k_F$ (here d is the effective spatial separation between the 2DESs). For our device, the measured densities give $B \approx 9\,T$ for this feature, in good agreement with experiment.

Wires of width 400 and 800 nm were fabricated using electron beam lithography and low-power reactive ion etching. A schematic diagram of the wires and contacts is shown in the inset to Fig. 3. We expect the actual width to be reduced by 50–100 nm by depletion. We performed magnetoresistance measurements on the wires for all three magnetic field orientations. For B_n, we use SdHO to obtain electron densities in the two wells of $2.7 \times 10^{15}\,m^{-2}$ and $1.9 \times 10^{15}\,m^{-2}$, indicating that after processing the quantum wells are still very close to balance. This is also reflected in the

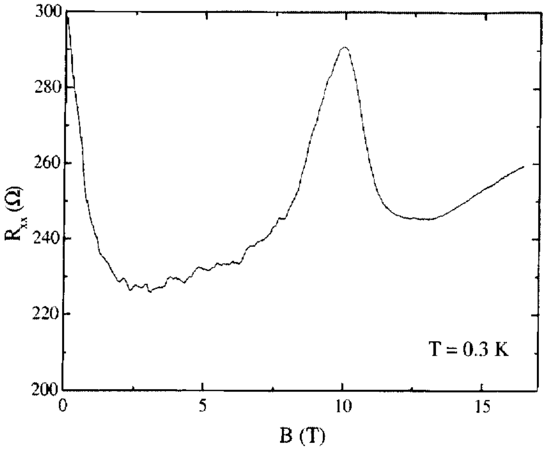

Fig. 2. In-plane magnetoresistance of the wire sample, with $B_{\perp}I$.

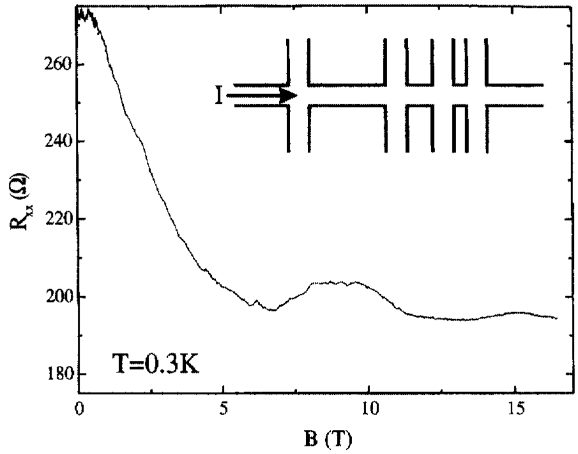

Fig. 3. In-plane magnetoresistance of the wire sample with $B_{||}I$. Inset is a schematic diagram of the 800 nm wire.

$B_{\perp}$ magnetoresistance at $T = 0.3$ K, as shown in Fig. 2 for a wire section of length 1 μm and nominal width 800 nm at $T = 0.3$ K. Comparing Fig. 1 and Fig. 2, we find that the RR is very similar in amplitude and width for both devices. This demonstrates that the wire fabrication does not introduce interwell scattering at the edges of the wire [9]. However, there are two major differences between the data for the Hall bar and for the wire. The first is that the RF is strongly enhanced and is, for the wire, a peak comparable in size to that at $B = 0$. The second is that we are able to observe UCF in the wire.

Fig. 3 shows the magnetoresistance of the same wire as in Fig. 2 but for $B_{||}$. The RR is still present with a similar amplitude but with a larger width. The increase in width is also seen in the Hall bar and is a consequence of the anisotropy of the scattering time caused by the interwell tunnelling [10]. The RF is weak, a qualitative difference to the $B_{\perp}$ case. We believe the highly anisotropic character of the RF in the wire is a size effect associated with increased scattering at the edges of the wire. Near the RF, the Fermi contour has the form shown in the inset to Fig. 1 where the axes are defined by B applied parallel to y. Since the elastic mean free path in the bulk material at $B = 0$ is $l \sim 10$ μm, the current in the wire is carried mostly by electrons very close to the k_x-axis, within an angle $\sim w/l \approx 6^{\circ}$ where w is the width of the wire. For $B_{\perp}$ the distortion of the Fermi contour for B near the RF means that there are fewer electrons near the k_x-axis to carry the current so that the resistance rises sharply. However, for $B_{||}$, the current-carrying electrons are not much affected by the distortion and only a small effect is observed, as in the Hall bar.

We turn now to the observation of UCF. In Fig. 2 and Fig. 3, reproducible fluctuations are visible on the magnetoresistance. Although their relative amplitude $\Delta R/R$ is small, the amplitude in conductance is close to e^2/h. This is seen in Fig. 4a and b, which show the conductance fluctuation amplitude at 0.3 K as a function of $B_{||}$ and $B_{\perp}$, respectively. It is also possible to observe UCF for B_n but in this case the UCF are quenched by the onset of SdHO at 0.25 T. However, their amplitude is the same as in Fig. 4 b and is determined by the phase-coherence length, l_{ϕ}. We estimate $l_{\phi} \approx 0.6$ μm at 0.3 K from a correlation function analysis of the fluctuations [11,12].

Also shown in Fig. 4c is the conductance of the wire with $B > 12$ T for the same field orientation as in Fig. 4b. Although there are clearly still some small fluctuations of conductance, they are at least an order of magnitude smaller than those at lower field and are largely due to noise. At this value of B, each 2DEG is localised in one of the quantum wells; tunnelling is suppressed and so are the fluctuations.

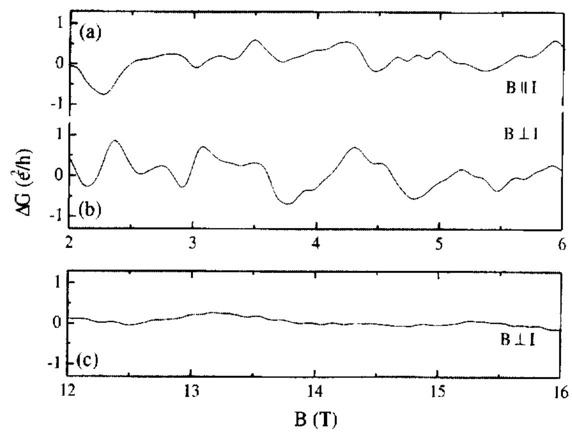

Fig. 4. Conductance fluctuations as a function of in-plane field. The fluctuations are UCF. Explanations for the three parts are in the text.

There are two possible mechanisms for the existence of UCF in this device. The first is an analogue of the conventional UCF in a 3D wire [13]. In this case the UCF are due to the flux enclosed by electrons which tunnel coherently from well to well. The other mechanism involves the distortion of the Fermi contour by the in-plane field. Because the electrons at the Fermi level are changing their energy and velocity slightly as a result of the distortion of the energy dispersion, their diffusive trajectories will also change, as will the UCF "magnetofingerprint". Both effects will disappear for $B > 10\,\mathrm{T}$. Clearly, the situation is very complicated. However, we know that the UCF for B_n must be conventional UCF, albeit in a quasi-ballistic system. We find that at $T = 0.3\,\mathrm{K}$ the Lee–Stone correlation field, ΔB_c is 4.7 mT. Using the relation [12]

$$\Delta B_c \approx \frac{h}{e} C \frac{1}{S}$$

(where C is a constant of order unity) we obtain $l_\phi \sim S^{1/2} \approx 0.6\,\mu\mathrm{m}$. For in-plane B applied in either direction relative to the current, we measure $\Delta B_c = 170\,\mathrm{mT}$. The ratio of the two values of ΔB_c is 36. Assuming that $\Delta B_c \propto l_\phi^{-2}$ for B_n, and that $\Delta B_c \propto (l_\phi d)^{-1}$, where d is the effective height of the wire, for the other orientations, we find $d = 17\,\mathrm{nm}$ which is in excellent agreement with the separation of the centres of the two quantum wells. In other words, the UCF in a system of parallel quantum wells are consistent with the theory developed for a 3D wire of height equal to the separation of the centres of the wells. We therefore conclude that the dominant mechanism producing the UCF is the flux enclosed by the tunnelling electrons, although clearly a full explanation will require both phenomena to be included.

In summary, we have investigated the magnetotransport properties of mesoscopic wires made from a system of parallel 2DEGs. We find evidence for a new size effect associated with the distortion of the energy dispersion. We also observe UCF which demonstrate directly the phase coherence of the electrons which tunnel between the two wells.

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