Phase coherence in double quantum well mesoscopic wires

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Abstract

We have observed conductance fluctuations (CF) on application of an in-plane magnetic field to 800 nm wide mesoscopic wires fabricated from modulation-doped GaAs/(AlGa)As double quantum well structures. This demonstrates the preservation of electron phase coherence in the presence of inter-well tunnelling and intra-well scattering. The CF disappear when the magnetic field becomes large enough to suppress tunnelling between the quantum wells, and the CF amplitude is lower in samples with thicker tunnel barriers. The wires also display a strong magnetoresistance feature as the quantum wells are decoupled by the in-plane magnetic field. This has been seen previously in macroscopic Hall bars, but is modified due to size effects in the wires. © 1998 Elsevier Science B.V. All rights reserved.

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Conductance fluctuations (CF) can be observed in the magnetoresistance of a mesoscopic system if there exist phase-coherent electron trajectories capable of enclosing magnetic flux [1]. For example, phase-coherent trajectories have long been known in two-dimensional electron systems, such as those confined at semiconductor heterojunctions or in quantum wells [2], but CF are not observed if the external magnetic field lies in the plane containing the 2D electrons. While phase coherence is preserved during elastic scattering in 2D electron transport, little is known about phase coherence during tunnelling processes. In the present work, we investigate mesoscopic wires containing two coupled 2D electron gases, and find convincing evidence for phase coherence when there is inter-well tunnelling as well as elastic scattering in each well. In addition, magnetoresistance features seen in macroscopic Hall bars are reproduced, but with modifications due to size effects.

A set of four samples (A–D) was grown by MBE, each sample comprising two 14.3 nm wide GaAs quantum wells separated by a thin Al 0.33 Ga 0.67 As barrier. The barrier thickness is different for each sample, varying from 2.2 to 4.9 nm (see Table 1). The quantum wells are sandwiched between modulation-doped Al 0.33 Ga 0.67 As barriers, with 40.3 nm thick spacers and doped layers of similar thickness with \( N_D = 1.3 \times 10^{18} \text{ cm}^{-3} \) (on the surface side) and \( N_D = 1.3 \times 10^{17} \text{ cm}^{-3} \) (on the substrate side).

Mesoscopic wires were fabricated with a width of 800 nm, and with voltage probes separated by 0.5, 1 and 3 \( \mu \text{m} \) lengths of wire. The side walls of the wires were defined by reactive ion etching. Macroscopic gated Hall bars were also fabricated.
for characterisation measurements. Electrical connections were made simultaneously to both quantum wells with diffused ohmic contacts. A dot of conducting silver epoxy was placed on top of some wires, providing a Schottky gate. The samples were measured by conventional low frequency AC techniques at temperatures down to 0.3 K. By mounting the wires on a rotating platform, the orientation of the magnetic field could be changed in situ.

The macroscopic Hall bars displayed behaviour typical of coupled quantum wells when magnetic field was applied perpendicular to the plane containing the quantum wells (\(B^\perp_{DQW}\)) \cite{3} or in the quantum well plane (\(B||_{DQW}\)) \cite{4–6}. With \(B^\perp_{DQW}\), Shubnikov-de Haas oscillations displayed nodes characteristic of the occupation of two subbands. The total carrier concentration and the symmetric–antisymmetric splitting \(\Delta_{\text{SAS}}\) obtained from the Shubnikov-de Haas oscillations are listed in Table 1. \(\Delta_{\text{SAS}}\) depends sensitively on the thickness of the barrier separating the quantum wells (\(d_B\)). The tabulated values of \(d_B\) are those which, when used in a self-consistent solution of Schrödinger and Poisson’s equations, give the measured \(\Delta_{\text{SAS}}\). The nominal barrier thickness differs by 10–30% from the tabulated \(d_B\).

We now turn to the magnetotransport properties of the wires, concentrating first on the sample with the thinnest barrier. All samples display qualitatively the same behaviour. With \(B^\perp_{DQW}\) and at temperatures less than \(~4\) K, conductance fluctuations were observed at low magnetic fields, followed by Shubnikov-de Haas oscillations which confirmed that both subbands remained occupied. By applying a small voltage (\(<0.1\) V) to the epoxy gate, the double quantum wells were easily brought into balance. A well-known classical size effect was also observed \cite{1}, namely a reduction in resistance due to magnetic suppression of backscattering that saturates when the conducting width of the wire \(W=2l_{\text{cycl}}\) where \(l_{\text{cycl}}\) is the cyclotron radius. This size effect gives \(W=630\) nm. Analysing the CF, we found that the correlation field \(\Delta B_c \approx 2.0\) mT and applying the relation \cite{7}

\[
\Delta B_c \approx \frac{\hbar}{eWl_{\phi}}
\]

gives the phase coherence length \(l_{\phi} \approx 3.3\) \(\mu\)m.

The sample was then rotated so that \(B||_{DQW}\). In this field orientation, as can be seen from the magnetoresistance traces in Fig. 1, it is necessary to distinguish between the application of the mag-

![Figure 1](image)

**Fig. 1.** Resistance at \(T=0.3\) K of sample \(A\) as a function of magnetic field \(B\) applied in the quantum well plane (a) perpendicular to the current direction and (b) parallel to the current direction. The insets show the Fermi discs of the two subbands at \(B=0\) (concentric circles) and close to \(B=B_{\text{high}}\).
netic field perpendicular to $(B \perp I)$ or parallel to the current $(B \parallel I)$. The most striking observation to be made in Fig. 1 for both $B \perp I$ and $B \parallel I$, is the existence of reproducible conductance fluctuations that persist up to a magnetic field $B_{\text{high}} = 8.6$ T. The CF have an amplitude of $\sim e^2/h$ and are observed whether the double quantum wells are in or out of balance. This result demonstrates that the electrons maintain phase coherence when tunnelling between quantum wells. For $B > B_{\text{high}}$, the CF disappear. At this field, the Fermi discs associated with the two subbands decouple. The effect of the in-plane magnetic field [8] is to introduce a relative shift between the two Fermi discs in $k$-space of $\Delta k = eBz_0/h$ where $z_0$ is the separation of the peak electron density in the two quantum wells. In the present case, the self-consistent calculation gives $z_0 = 19$ nm and $n \approx 2.3 \times 10^{11}$ cm$^{-2}$ in each subband, so the Fermi discs should decouple when $B = 8.3$ T, close to the value observed. In this field orientation, the correlation field $\Delta B_c = 70$ mT. Taking the value for $l_\phi$ obtained previously, and considering now

$$\Delta B_c \approx \frac{h}{e} \frac{1}{dl_\phi},$$

we obtain $d = 18$ nm for the extent of the electron trajectory in the direction normal to the quantum well plane. This agrees well with the 19 nm separation of the electron distributions in the two wells given by the self-consistent calculation.

The effect of the thickness of the barrier separating the quantum wells can be seen in Fig. 2. Here conductance fluctuations are plotted for all four samples over two ranges of in-plane field, $B < B_{\text{high}}$ and $B > B_{\text{high}}$. Any weak variations in background resistance have been removed. In all cases, the suppression of CF can be seen in the high field range. In the low field range, the CF amplitude reduces strongly with increasing barrier thickness $d_B$. Note that each trace is recorded over a segment of wire of the same length (0.5 µm), at the same temperature (0.3 K), and in samples with similar phase coherence lengths ($l_\phi \sim 3$ µm). The correlation field $\Delta B_c$ shows no systematic dependence on barrier thickness, with $\Delta B_c = 70 \pm 10$ mT for all samples. This is reasonable because $d_B$ changes by $\sim 2$ nm, which is much smaller than the overall separation of the centres of the two wells. It is interesting to note that the changes in barrier thickness are tiny in comparison with any other length scale in the system. Yet because of the exponential sensitivity of the tunnelling interaction, changes in the barrier have a strong influence on CF amplitude. The thicker barrier means a reduced tunnelling rate, so the electrons take longer to traverse the closed trajectories, spending more time within a particular well and having a greater probability of undergoing a phase-breaking inelastic scattering event. Thus the CF amplitude is determined by the interplay between the tunnelling rate and the rate of intra-well inelastic scattering.

Finally we briefly discuss two additional features in the magnetoresistance. The first is the low field resistance resonance, previously seen in macroscopic Hall bars [4], and ascribed to the rapid reduction in tunnelling as the Fermi discs start moving from concentricity.
the feature when $B \parallel I$ has also been noted [4]. A second feature is observed at $B_{\text{high}}$, but only when $B \perp I$. This high field feature is qualitatively different to that observed in macroscopic Hall bars [5,6], where the resistance first decreases and then increases as the Fermi discs decouple and the Fermi level moves through the partial energy gap [9]. In addition, the resistance anomaly in the macroscopic system is relatively smaller, and has a weaker dependence on the relative directions of current and magnetic field. We explain qualitatively the behaviour in the wires by considering the Fermi surface close to $B_{\text{high}}$ and the influence of the sample edges. Because of diffuse electron scattering at the wire edges, electrons travelling along the axis of the wire will make a greater contribution to the conductivity. These electrons occupy states indicated by shading on the Fermi surface (see insets to Fig. 1). In the macroscopic case, states all around the Fermi surface are important. When $B \parallel I$ the shaded electron states are unaffected by the uncrossing of the Fermi discs. There is virtually no change in background resistance at $B_{\text{high}}$, but nevertheless the CF quench, indicating the absence of tunnelling. However for $B \perp I$, there are shaded states that lie at a saddle point in $k$-space where the electron group velocity is low and there is also a logarithmic singularity in the density of states. Hence there is increased resistance as the Fermi discs decouple.

To conclude, we have observed CF in mesoscopic double quantum well wires on application of an in-plane magnetic field. This shows directly that electrons delocalised between the two wells maintain phase coherence over a path comprised of free particle motion in the wells coupled by phase-coherent inter-well tunnelling transitions. The CF amplitude decreases rapidly with increasing tunnel barrier thickness and the CF are suppressed completely when the wells are decoupled by a sufficiently large in-plane magnetic field $B_{\text{high}}$. The wires also show a resistance anomaly at $B_{\text{high}}$ which is qualitatively different to that observed in macroscopic systems, and which is explained as a classical size effect.

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References