Superlattices and Microstructures, Vol. 22, No. 3, 1997

Tuning the inter-subband tunnelling and universal conductance fluctuations with an in-plane magnetic field in the 'quantum transport regime'

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(Received 15 July 1996)

Magnetotransport measurements are reported on mesoscopic wire samples containing tunnelling-coupled two-dimensional electron gases (2DEGs) confined on opposite sides of a single wide quantum well. An in-plane magnetic field 'tunes' the tunnelling between the 2DEGs and controls the number of occupied magnetoelectric subbands. It is found that in mesoscopic wires extra disorder quenches the resistance resonance observed in macroscopic Hall-bars. Universal conductance fluctuations are observed in a parallel magnetic field, reflecting the three-dimensional nature of electron trajectories, even in the limit of only one occupied subband.

The properties of two-dimensional electron gases (2DEGs) in a parallel magnetic field have been investigated in both the semiclassical regime described by the Boltzmann equation [1, 2], and also in the quantum regime where universal conductance fluctuations (UCF) and weak localisation occur [3]. Transport in spatially separated 2DEGs coupled by tunnelling and Coulomb interaction has been studied in detail [4–6] in both regimes. It is possible to 'tune' the tunnelling coupling with an in-plane magnetic field [5], and to control the number of occupied subbands in multi-subband systems [7]. In this paper we explore UCF in a parallel magnetic field, where we have used the field to tune both the tunnelling coupling and the number of occupied subbands.

Our MBE-grown samples comprise a 407 Å-wide quantum well (QW) confined between two $Al_{0.3}Ga_{0.7}As$ barriers, each with a 407 Å modulation doped layer ($N_D = 1.33 \times 10^{18}$ cm^{-3}), separated from the QW by a 76 Å undoped buffer layer. Three QW subbands (E_0, E_1, E_2) are occupied at zero field [8], with densities $n_0 = 1 \times 10^{12}$ cm^{-2}, $n_1 = 0.5 \times 10^{12}$ cm^{-2} and $n_2 = 0.1 \times 10^{12}$ cm^{-2}; the measurable mobilities in a macroscopic Hall-bar are $\mu_0 = 1.0$ m^2 V^{-1} s^{-1}, $\mu_1 = 20.4$ m^2 V^{-1} s^{-1}, with $\mu_2 \leq \mu_1$. The two lowest subbands (E_0, E_1) form the parallel 2DEGs, separated by an effective distance $d = 32$ nm, obtained from a self-consistent calculation of the distance between wavefunction peaks [8]. Mesoscopic wires were fabricated with lithographic widths 800 nm ('wire A') and $W = 400$ nm ('wire B').

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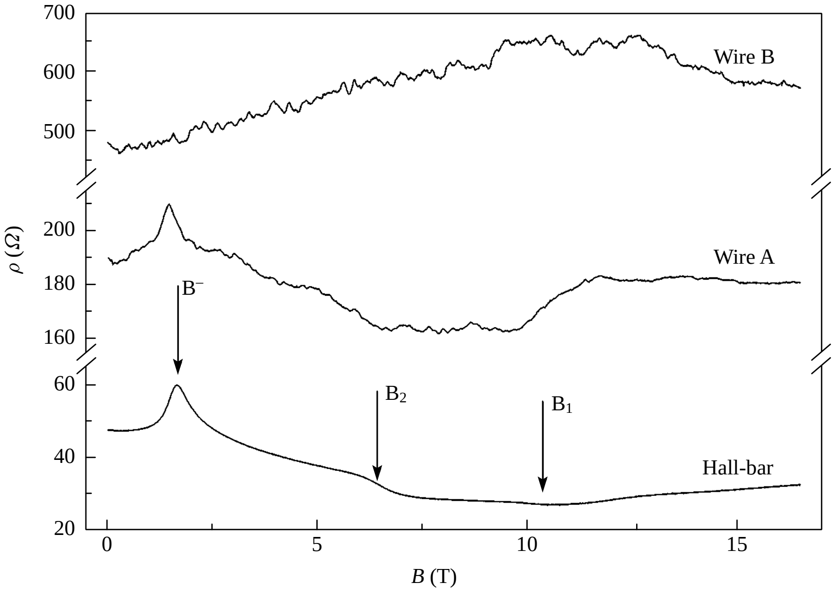

Fig. 1. Magnetoresistance in a magnetic field, B, applied in the plane of the QW and normal to the current for a macroscopic Hall-bar sample and wires A and B.

Figure 1 shows the magnetoresistivity, $\rho(B)$, for the Hall-bar, wire A and wire B with the magnetic field, B, applied in the QW-plane perpendicular to the current. First, we focus on the increase of $\rho(0)$ when the width, W, of the structure becomes smaller. The deep-etched wire mesa is a source of increased disorder over that in the Hall-bar sample since it gives rise to diffusive boundary scattering. The low-temperature mobility of the E_i-subband is expected to diminish if the elastic mean free path in the Hall-bar, l_i, is larger than W. Therefore, we do not expect any change for the E_0-subband, with $l_0 = 165$ nm. However the E_1-subband, which carries 90% of the current in the Hall-bar, has a strongly reduced mobility, since $l_1 = 2.8\ \mu$m. Assuming a constant mobility in the E_0-subband, we estimate a decrease to $l_1 \approx 540$ nm for wire A and $l_1 \approx 80$ nm for wire B. The latter value shows that for wire B it is more realistic to assume $l_0 \approx l_1$ leading to $l_1 \approx 129$ nm.

Before discussing the $\rho(B)$ of the wires further, we consider the effect of B on the system. From an investigation of the Hall-bar sample [8] we know that the tunnelling coupling between the two interfaces of our QW is extremely weak for the E_0- and E_1-subbands at $B = 0$ T. At a field $B^- = 1.6$ T, however, tunnelling is 'switched on' for electrons at the Fermi-energy due to the relative shift $\Delta k = deB/\hbar$ of the two Fermi-circles (with Fermi wavevectors $k_F^{(0)}$, $k_F^{(1)}$). The Fermi-circles touch internally at B^-, where $\Delta k = k_F^{(0)} - k_F^{(1)}$. Similarly, tunnelling is 'switched off' at $B > B^+ \sim 17$ T when $\Delta k \approx k_F^{(0)} + k_F^{(1)}$, i.e. where the Fermi-circles touch externally. Within the range $B^- < B < B^+$, the number of occupied magnetoelectric subbands changes at $B_2 = 6$ T and $B_1 = 10.5$ T where respectively the E_2- and the E_1-subbands are depopulated due to the diamagnetic energy shift.

The strong mobility-asymmetry between the E_0- and the E_1-subband in the Hall-bar causes a resistance resonance (RR) at B^- (see Fig. 1) [8]. The relative amplitude of the RR, $\Delta R/R$, can be estimated under the assumption that at $B = 1.6$ T a fraction f_i of states in each subband is extended over the full QW-width. Thus the average scattering rate of these states is $1/\bar{\tau} = \frac{1}{2}(1/\tau_0 + 1/\tau_1)$, whereas all the other states are unaffected and scatter with the rate $1/\tau_i$. From the results of the self-consistent calculation of the wavefunctions in a parallel magnetic field we deduce the values of $f_{0,1}$ to be $f_0 = 0.15$ and $f_1 = 0.27$. Neglecting the E_2-subband,

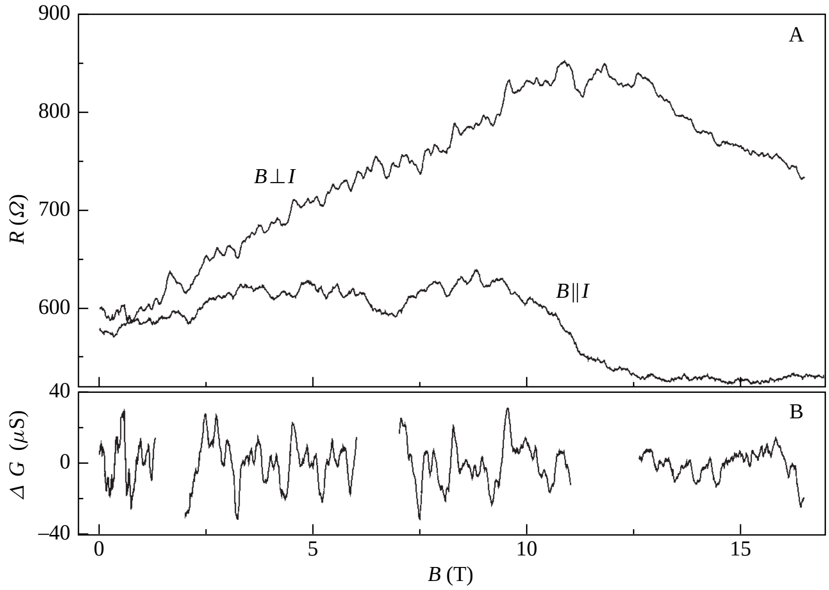

Fig. 2. A Two magnetoresistance curves from wire B. In both, B is applied parallel to the 2DEGs, but the orientation of B relative to I is changed. B The bare UCF in wire B for $B \perp I$ in the different magnetic field ranges of interest, as obtained by subtracting a smooth background from the original $R(B)$.

the above argument leads to

$$\frac{\Delta R}{R} = \frac{n_0\tau_0 + n_1\tau_1}{(1 - f_0)n_0\tau_0 + (1 - f_1)n_1\tau_1 + (f_0 n_0 + f_1 n_1)\bar{\tau}}. \tag{1}$$

If we set $n_0 = n_1$ and $f_0 = f_1 = 1$ we recover the familiar expression $\Delta R/R = (\tau_1 - \tau_0)^2/(4\tau_1\tau_0)$ used by other authors [6, 9] for coupled QW samples with balanced electron densities. From Eqn (1) we estimate the relative amplitude of the RR to be 28% for the Hall-bar, in excellent agreement with experiment. It can be seen in Fig. 1 that $\Delta R/R$ is quenched with decreasing wire width W. From the reduced mean free path l_1 in the wires we determine the scattering time τ_1 and use it in Eqn (1). We obtain $\Delta R/R = 10\%$ for wire A and $\Delta R/R = 0$ for wire B, again in agreement with the experiment (no adjustable parameters are used for Eqn (1)). We conclude that the decreasing mobility-asymmetry in the wire samples leads to the quenching of $\Delta R/R$.

It can be seen in Fig. 1 that reproducible UCF occur in the two wire samples. For *independent* 2DEGs in the quantum limit, no UCF would be expected in this in-plane field geometry, because the electron trajectories would enclose no flux. On the other hand, it has been shown that in a sample with five occupied subbands electron motion is three-dimensional and UCF occur with an in-plane field [3]. In our structure we can explore how many subbands are actually required to maintain the three-dimensional nature of electron trajectories.

Figure 2A shows the magnetoresistance of wire B with $B \perp I$ and $B \| I$. In Fig. 2B the smoothly varying background current is subtracted from the $B \perp I$ curve. UCF occur even below B^- where the parallel 2DEGs should be decoupled. Furthermore the depopulation of the uppermost subband has no measurable influence on the amplitude, nor on the characteristic period, ΔB, of the fluctuations. Above 12.5 T, when only the lowest subband remains occupied, UCF are still observed *in sharp contrast to our experience with narrow QWs*, but the amplitude is now reduced by a factor of about two.

The typical period, ΔB, of the fluctuations in $R(B\|I)$ is $\sim$1.3 times larger than in $R(B \perp I)$ in accordance with the maximum available areas: $W \times d$ for $B\|I$, and $l_\phi \times d$ for $B \perp I$ (where l_ϕ is the phase coherence length). When B is applied *perpendicular to the 2DEGs* the typical ΔB is four times smaller than in the $B\|I$ configuration. In this case the relevant area is $l_\phi \times W$. The ΔB's scale in the same way as for a three-dimensional wire [10] reflecting the three-dimensional nature of the electron trajectories as long as at least two subbands are occupied.

For an explanation of the occurrence of UCF at fields below B^- we consider two arguments. First, even if there is no tunnelling coupling between the E_0- and the E_1-subbands, the two interface states can still couple at the Fermi-energy via the slightly occupied E_2-subband which allows electrons to traverse the QW. Second, it was recently pointed out by Vasko and Raichev [9] that disorder in the 2DEGs leads to a modification of the tunnelling coupling. Potential fluctuations in the 2DEGs can locally couple the E_0- and E_1-interface states via tunnelling, even below B^-. This effect will be stronger the more disordered the 2DEGs are.

We have no explanation for the observed reduction in the UCF amplitude at fields above 12.5 T. We can, however, argue for the persistence of the three-dimensional nature of electron trajectories if we consider that the magnetic length $l_c = \sqrt{\hbar/(eB)}$ beyond $B = 12.5$ T is much smaller than the width of the QW. In this regime, states with different k_y $(B\|x)$ correspond to different positions between the two interfaces of the QW. Elastic scattering between different k_y is therefore equivalent to a change in position in the z-direction. This type of three-dimensional motion must eventually be suppressed beyond B^+, where the E_0-subband Fermi-contour consists of two independent circles, i.e. two independent components located at opposite interfaces. The high magnetic fields required to observe this transition were not available for the reported measurements.

To summarise, we have performed electrical transport experiments on mesoscopic wire samples containing parallel 2DEGs confined at opposite interfaces of a 407 Å-wide QW. The additional diffusive boundary scattering introduced by the fabrication process diminishes the subband mobilities and quenches the resistance resonance observed in macroscopic Hall-bar samples. The number of occupied subbands was tuned by applying a magnetic field in the plane of the QW. In the wires the three-dimensional character of the UCF is maintained even with only one magnetoelectric subband occupied since the states confined to the opposite interfaces are coupled by tunnelling.

Acknowledgements—This work was supported by the EPSRC (UK). LE is supported by an EPSRC senior fellowship.

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