



ELSEVIER

Physica B 249–245 (1998) 157–161

PHYSICA B

Closely separated one-dimensional wires: coupled ballistic conduction, wave function hybridization and compressibility investigations

I.M. Castleton*, A.G. Davies, A.R. Hamilton, J.E.F. Frost, M.Y. Simmons, D.A. Ritchie,
M. Pepper

Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK

Abstract

We report the experimental study of a system comprising two parallel quasi-one-dimensional (1D) ballistic wires formed in a GaAs-Al_xGa_{1-x}As double quantum well structure. A unique surface gate geometry allows the device to be tuned smoothly from a configuration comprising a pair of vertically aligned 1D ballistic wires, to a single 1D ballistic wire in either the upper or lower 2DES. We investigate coupled ballistic conduction in two samples with contrasting wire separations (35 and 300 Å). The strongly coupled sample exhibits a cross-over from double to single wire conduction as the number of occupied 1D subbands is reduced. The weakly coupled sample is used to observe directly variations in the compressibility of a single ballistic channel arising from the discrete 1D density of states. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: One-dimensional; Coupled quantum wires

1. Introduction

The use of sub-micron Schottky gates to confine the two-dimensional electron system (2DES) formed in a GaAs-Al_xGa_{1-x}As heterojunction electrostatically into a quasi-one-dimensional (1D) conducting channel is well-established, and has led to the realization of 1D transport [1] and the observation of quantized 1D ballistic conduction

[2]. By analogy with double-layer 2DESs which have revealed a range of new physical phenomena [3], double-layer 1D systems comprising two closely separated, parallel, quasi-1D channels should prove a versatile extension to the single 1D system and have already attracted much theoretical attention with the prediction of unique transport properties, including a proposed superconducting phase [4]. Strongly coupled double quantum wire structures have also been discussed from an applied point-of-view in the context of electron interferometers [5].

*Corresponding author. Fax: +44 1223 337271; e-mail: imc12@cus.cam.ac.uk.

We present the first experimental study of double-layer ballistic 1D systems formed in GaAs-Al_xGa_{1-x}As double quantum well (DQW) structures in which each quasi-1D channel can be controlled independently between definition and pinch-off by the surface gate geometry. Since the 1D channels are separated by an Al_xGa_{1-x}As barrier which is precisely defined on an atomic scale by molecular beam epitaxy (MBE), the wires can be positioned much closer together than possible in laterally patterned double 1D systems formed in a single 2DES [6].

2. Experimental

Two DQW structures were employed, each comprising two 150 Å-wide GaAs quantum wells separated by an undoped Al_{0.33}Ga_{0.67}As barrier of width 300 Å in sample 1 (MBE layer T225) and 35 Å in sample 2 (MBE layer T211). Silicon-doped Al_{0.33}Ga_{0.67}As layers, offset by undoped Al_{0.33}Ga_{0.67}As spacer layers, were situated either side of the double quantum well in both samples. The DQW structures were processed into a Hall bar geometry with AuGeNi alloy electrical contacts which connected both 2DESs. The total carrier density and mobility (unilluminated) of the DQWs were around $2.6 \times 10^{11} \text{ cm}^{-2}$ and $10^6 \text{ cm}^2/\text{Vs}$, respectively. The Fig. 1a inset shows the NiCr–Au surface Schottky gate configuration fabricated by electron-beam lithography – the split-gate (SG) defines a 1D channel in each 2DES whilst the mid-gate (MID) principally controls the upper wire electron density. In sample 1 (sample 2), the split-gate arm separation was 0.8 μm (1.2 μm) and the mid-gate width was 0.3 μm (0.5 μm). The split-gate length was 0.5 μm in both samples. Two-terminal conductances were measured at 1.5 K (sample 1) and 500 mK (sample 2) using standard AC lock-in techniques.

A 10 μm-wide gate (FULL) extending across the width of the Hall bar could be used to selectively pinch-off the upper 2DES in the wide-barrier device (sample 1). The Fig. 1b inset shows the conductance of sample 1 as the full-gate is swept with the other gates grounded; a two-stage pinch-off is observed with the upper 2DES depleting at

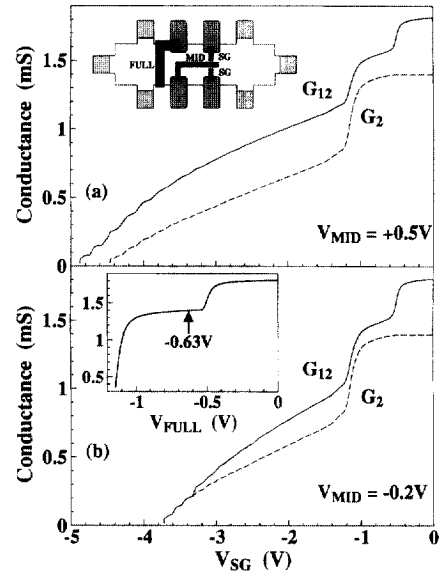


Fig. 1. G_{12} (solid lines) and G_2 (dashed lines) versus V_{SG} for (a) $V_{MID} = +0.5$ and (b) $V_{MID} = -0.2$ V, for sample 1. Insets show schematic Hall bar geometry and full-gate pinch-off characteristic; application of $V_{FULL} = -0.63$ V depletes the upper 2DES allowing measurement of lower wire conductance.

$V_{FULL} = -0.55$ V followed by the lower 2DES depleting at $V_{FULL} = -1.15$ V. Since inter-layer tunnelling is prevented by the 300 Å barrier, application of $V_{FULL} \lesssim -0.55$ V ($V_{FULL} = -0.63$ V was used here) results in the source-drain excitation voltage being applied across the lower 1D channel only, even if both 1D channels are present, enabling the conductance of the lower channel to be measured independently.

3. Coupled ballistic conduction

Fig. 1a shows the conductance of sample 1 as a function of split-gate bias (V_{SG}) for mid-gate bias $V_{MID} = +0.50$ V. The solid line is the conductance of both layers in parallel (G_{12}), whilst the dashed line is the conductance of just the lower layer (G_2) obtained by application of $V_{FULL} = -0.63$ V. As V_{SG} is made increasingly negative, the sharp drops in G_{12} indicate the definition of a quasi-1D channel, first in the upper 2DES at $V_{SG} = -0.60$ V (no corresponding feature in G_2) and then in the lower

2DES at $V_{SG} = -1.20$ V. For -1.20 V $\geq V_{SG} \geq -4.50$ V, both traces show a reduction in sample conductivity indicating the depopulation of both quasi-1D channels. For $V_{SG} < -4.50$ V, G_2 is zero indicating that the lower wire is fully depleted; only the upper quasi-1D wire is present until $V_{SG} = -4.90$ V, where G_{12} becomes zero, and the device is completely pinched off. Fig. 1b shows the conductance traces for $V_{MID} = -0.20$ V. As before, the split-gate defines a quasi-1D channel first in the upper layer, and then in the lower layer. However, at $V_{SG} = -3.30$ V, G_{12} joins the G_2 trajectory demonstrating that the upper 1D wire has pinched-off. The lower wire ultimately pinches off at $V_{SG} = -3.75$ V. The mid-gate/split-gate combination can thus tune the device into a configuration comprising a pair of vertically-aligned quasi-1D channels, or a single quasi-1D channel in either the upper or lower 2DES.

Fig. 2a shows G_{12} for sample 1 as a function of V_{SG} for a series of V_{MID} from $+0.50$ to -0.48 V in 0.02 V steps [7]. Three distinct regions are ob-

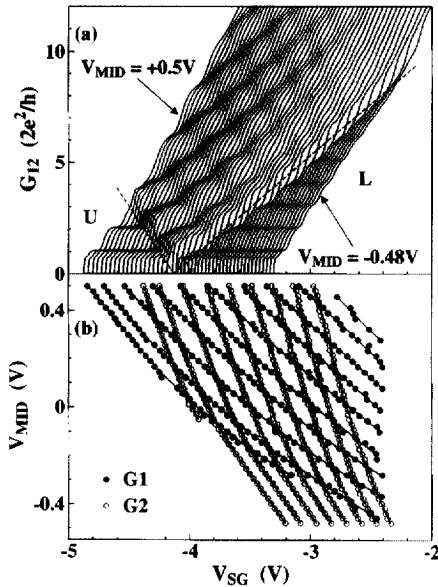


Fig. 2. (a) G_{12} versus V_{SG} for sample 1 for a series of V_{MID} . A single wire conducts in regions U and L delineated by dashed lines from the region in which both wires conduct in parallel. (b) $\partial G_1/\partial V_{SG}$ (●) and $\partial G_2/\partial V_{SG}$ (○) maxima. The rising-edge trajectories of the two wires cross smoothly.

served. The triangular regions at the bottom left and right labelled 'U' and 'L' arise from a single quasi-1D channel in either the upper or lower layer, respectively, with the other channel pinched off. Both channels exhibit strong ballistic conductance plateaux quantized in steps of $2e^2/h$, in addition to structure at $0.7(2e^2/h)$ which has recently been attributed to a zero-magnetic-field spin polarization induced by electron–electron interactions [8]. In the central region, two quasi-1D wires are present and conduct in parallel with a total conductance equal to the sum of the conductance of each wire.

Sun et al. [9] calculated the energy levels of two infinitely long, parallel, quasi-1D conductors of 2000 Å separation in the limit of zero inter-wire tunnelling and found that under certain conditions, adjacent levels could approach one another at the chemical potential and even coincide, becoming locked together. Fig. 2b shows the position of the inter-plateau rising-edges, corresponding to 1D density-of-states (DOS) maxima, in G_1 (upper wire conductance) and G_2 as a function of V_{MID} and V_{SG} , obtained from the derivative of the individual conductance traces. The fitted curves show the trajectory of each inter-plateau rising-edge and it is seen that trajectories from upper and lower wires simply cross with no evidence of locking. The spacing of conductance features in gate bias may not necessarily reflect variations in energy level separation since maxima in the 1D DOS pin at the chemical potential [10]. However, a locking of adjacent energy levels should lead to extended regions over which the conductance jumps by $4e^2/h$ which we do not observe in this analysis.

4. Wavefunction hybridization

Fig. 3a and b show $\partial G_{12}/\partial V_{SG}$ for samples 1 and 2, respectively – light regions indicate ballistic plateaux, dark regions indicate rising-edges between plateaux (the white circles (○) are discussed later); 'U' and 'L' indicate the presence of a single quasi-1D wire in the upper or lower 2DES. In the weakly coupled sample, single-wire regions are completely separated by the double-wire region (Fig. 3a) and a V-shaped boundary (indicated explicitly in Fig. 2a) delineates the three regions. In the strongly

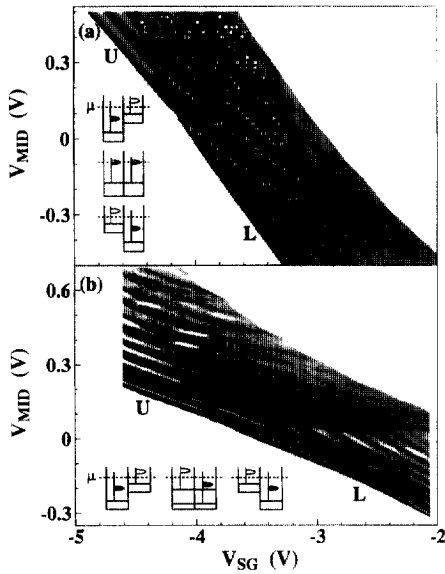


Fig. 3. $\partial G_{1,2}/\partial V_{SG}$ for (a) sample 1 and (b) sample 2. Light regions indicate ballistic plateaux, dark regions indicate rising-edges. Schematic insets show lowest 1D subbands as conduction transfers between wires. The ΔV_{SG} minima of the lower wire (○) follow upper wire rising-edge trajectories.

coupled sample, however, this boundary lifts away from zero conductance, and single-wire behaviour is observed across the entire V_{MID} range for $G_{1,2} \lesssim 4e^2/h$ (Fig. 3b). The lowest two 1D subbands transfer smoothly between the upper and lower quantum wells.

In a DQW structure in which the two wells are identical ('balanced'), the two lowest subbands are the symmetric and antisymmetric eigenstates which are delocalized equally across both quantum wells and are separated by the tunnelling gap Δ_{SAS} . Under the influence of an external electric field, however, the wave functions of the two lowest subbands become increasingly localized in the individual wells [10]. The Fig. 3 insets show schematically the quantum well subband energies, the lowest two 1D subbands and the chemical potential (μ) as the split-gate/mid-gate combination takes the system along a trajectory of $G_{1,2} = 2e^2/h$. In sample 1, there is negligible tunnelling gap owing to the wide $Al_{0.33}Ga_{0.67}As$ barrier, and so the lowest 1D subbands cross at the chemical potential for conduction to transfer from the lower to the upper well,

temporarily destroying the quantized conductance (at the tip of the V-shaped boundary in Fig. 3a). In sample 2, however, the lowest 1D subbands become progressively delocalized across both quantum wells as the balance point is approached and so conduction transfers smoothly from the lower to the upper well maintaining ballistic quantization. The relative size of the 1D subband separation and the tunnelling gap ($\Delta_{SAS} \approx 1$ meV in sample 2) governs the number of 1D subbands that can transfer in this way and the extent to which the V-shaped boundary lifts from zero conductance.

5. Investigations of finite 1D compressibility

Fig. 4a shows G_2 as a function of V_{SG} for a series of V_{MID} in 0.02 V steps for sample 1. When the upper channel is populated, it partially screens the lower channel from the mid-gate bias and the effect of the incremental change in V_{MID} on G_2 is smaller

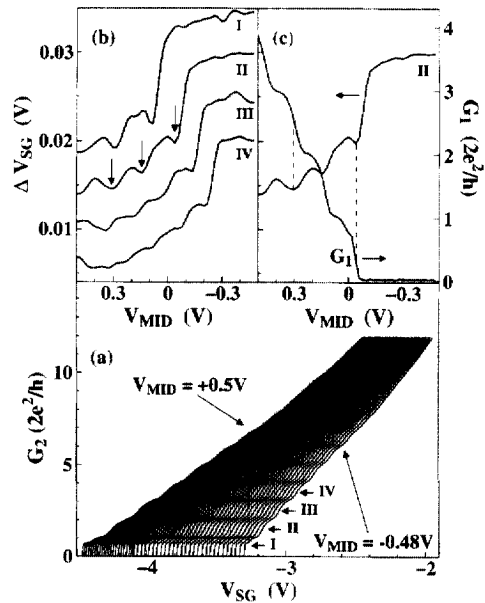


Fig. 4. (a) G_2 versus V_{SG} for a series of V_{MID} for sample 1. (b) ΔV_{SG} versus V_{MID} for the four G_2 indicated in (a) – traces I, III, IV are offset for clarity. The minima positions (arrowed) are plotted (○) in Fig. 3a for a range of G_2 . (c) ΔV_{SG} minima correspond to G_1 inter-plateau rising-edges (peaks in 1D DOS).

(successive sweeps are closely spaced – left of plot) than when the upper channel is pinched-off (sweeps are more widely spaced – right of plot). However, the fact that the lower channel is affected at all by V_{MID} when the upper channel is populated indicates that the upper channel has finite screening ability and hence a finite compressibility. In a procedure introduced by Eisenstein et al. [11], the 2D DOS and compressibility of a 2DES is obtained directly in a DLES by using the lower 2DES to measure the electric field penetrating the upper 2DES. This method has advantages over earlier capacitance techniques in which the desired 2D contribution to the capacitance can be swamped by a large geometric term. Previous capacitance measurements of quasi-1D channels identified structure in the total sample capacitance (or its voltage derivative) reflecting the 1D DOS [12]. However, both studies averaged over arrays of several hundred, long (180–200 μm), parallel, quasi-1D wires. We demonstrate that we can observe the changes in the screening (and hence the compressibility) of a *single ballistic channel* arising from its discrete 1D DOS.

In an analysis in which G_2 is held constant, we assume that variations in the mid-gate field penetrating the upper wire and incident on the lower wire are compensated by changes in the split-gate field which confines the lower wire. From the sideways shift between neighbouring sweeps in Fig. 4a, we obtain $\Delta V_{\text{SG}}(V_{\text{MID}})$ for fixed G_2 . Fig. 4b shows plots of ΔV_{SG} vs V_{MID} for the four selected values of G_2 indicated in Fig. 4a – traces I, III and IV are offset for clarity. For very negative V_{MID} , the upper channel is depleted and ΔV_{SG} is relatively featureless. As V_{MID} is increased however, a distinct minimum is observed in ΔV_{SG} as the first 1D subband in the upper channel becomes populated. Further minima are observed, each coincident with the rising-edge between ballistic plateaux in upper channel conductance; this is demonstrated explicitly in Fig. 4c which shows one ΔV_{SG} trace together with the corresponding G_1 trace. The positions of the ΔV_{SG} minima obtained for a range of G_2 are shown

(\circ) in Fig. 3a and demonstrate that although these features are obtained entirely from an analysis of the lower channel conductance, they follow the trajectories of the inter-plateau rising-edges of the upper channel. ΔV_{SG} indicates the amount of mid-gate field penetrating the upper wire and so minima in ΔV_{SG} occur when the upper wire has maximum compressibility and can screen the field most efficiently. This is when a peak in the upper channel DOS is at the chemical potential.

We thank Dr. C.H.W. Barnes, Dr. C.J.B. Ford and Dr. C.G. Smith for helpful discussions. A.G.D. and D.A.R. acknowledge the support of the Royal Society and TCRC, respectively. This work was funded by the EPSRC (UK).

References

- [1] T.J. Thornton et al., Phys. Rev. Lett. 56 (1986) 1198; K.-F. Berggren et al., Phys. Rev. Lett. 57 (1986) 1769.
- [2] B.J. van Wees et al., Phys. Rev. Lett. 60 (1988) 848; D.A. Wharam et al., J. Phys. C 21 (1988) L209.
- [3] For review see, J.P. Eisenstein, in: D. Heiman (Ed.), High Magnetic Fields in Semiconductor Physics, World Scientific, Singapore, 1995, p. 78 and references therein.
- [4] see, for example, T. Kimura et al., Phys. Rev. B 49 (1994) 16852; *ibid* B 51 (1995) 13860.
- [5] M. Okuda, J. Appl. Phys. 78 (1995) 1039 and references therein.
- [6] C.G. Smith et al., J. Phys. Condens. Mat. 1 (1989) 6763; P.J. Simpson et al., Appl. Phys. Lett. 63 (1993) 3193.
- [7] Two-terminal measurements of single 1D channels require the elimination of the 2D series contribution to obtain the correct channel conductance. This is more complicated in double-layer structures but a model in which the dominant series resistance contribution originates in the ohmic contacts was the most successful for our data, and the corrected conductances are presented here. No free parameters are introduced in this analysis.
- [8] K.J. Thomas et al., Phys. Rev. Lett. 77 (1996) 135.
- [9] Y. Sun, G. Kirczenow, Phys. Rev. Lett. 72 (1994) 2450.
- [10] A.G. Davies et al., Phys. Rev. B 54 (1996) 17331R.
- [11] J.P. Eisenstein et al., Phys. Rev. Lett. 68 (1992) 674; Phys. Rev. B 50 (1994) 1760.
- [12] T.P. Smith et al., Phys. Rev. Lett. 59 (1987) 2802; H. Drexler et al., Phys. Rev. B 49 (1994) 14074.