Experimental studies of Coulomb drag between ballistic quantum wires

2001 J. Phys.: Condens. Matter 13 3389

(http://iopscience.iop.org/0953-8984/13/14/312)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **13** (2001) 3389–3402 www.iop.org/Journals/cm PII: S0953-8984(01)19085-5

Experimental studies of Coulomb drag between ballistic quantum wires

P Debray[1], **V Zverev**[2], **O Raichev**[3], **R Klesse**[4], **P Vasilopoulos**[5] **and R S Newrock**[6]

[1] Service de Physique de l'État Condensé, CEA Saclay, 91191 Gif-sur-Yvette, France
[2] Institute of Solid State Physics RAS, Chernogolovka, Moscow Region, 142432, Russia
[3] Institute of Semiconductor Physics, NAS Ukraine, Prospekt Nauki 45, Kiev, 03028, Ukraine
[4] Universität zu Köln, Institut für Theoretische Physik, D-50937 Köln, Germany
[5] Concordia University, Department of Physics, Montréal, Québec, Canada, H3G 1M8
[6] Department of Physics, University of Cincinatti, OH 45221-0011, USA

E-mail: debray@drecam.saclay.cea.fr

Received 14 November 2000, in final form 16 February 2001

Abstract

The Coulomb drag between two spatially separated one-dimensional (1D) electron systems in lithographically fabricated 2 μm long quantum wires is studied experimentally. The drag voltage V_D shows peaks as a function of a gate voltage which shifts the position of the Fermi level relative to the 1D subbands. The maximum in V_D and the drag resistance R_D occurs when the 1D subbands of the wires are aligned and the Fermi wave vector is small. The drag resistance is found to decrease exponentially with interwire separation. In the temperature region 0.2 K $\leqslant T \leqslant$ 1 K, R_D decreases with increasing temperature in a *power-law* fashion $R_D \propto T^x$ with x ranging from -0.6 to -0.77 depending on the gate voltage. We interpret our data in terms of the Tomonaga–Luttinger liquid theory.

1. Introduction

Moving charges in a conductor exert a Coulomb force on the charge carriers in a nearby conductor and induce a drag current in the latter through momentum transfer. This phenomenon, known as Coulomb drag (CD), between spatially isolated, closely spaced electron systems has been the focus of considerable attention in the past few years. The interest in CD arises mostly from the fact that it offers the unique possibility of investigating electron–electron interaction in low-dimensional systems through measurements of the transport coefficients. The CD between two-dimensional (2D) electron systems [1] has been extensively studied [2] both experimentally and theoretically. The quantity usually measured in experiments is the drag resistance $R_D = -V_D/I$, where I is the current in one ('drive') of the layers and V_D is the voltage developed in the other ('drag') layer, when no current is allowed to flow in the latter. The temperature, layer separation, and electron-density dependencies of the drag resistance, the influence of disorder and of a magnetic field, as well as the manifestations of collective excitations and electron–phonon interaction have been investigated [2]. The basic physics involved in the description of R_D is now well understood, except in the case of the CD in the quantum Hall regime where some questions remain unresolved [3, 4].

Recently, a growing interest is being shown in the CD between one-dimensional (1D) electron systems formed in spatially separated quantum wires. In early theoretical papers [5, 6] it was shown that due to the restrictions imposed by the momentum and energy conservation rules, the drag at low temperatures has a sharp maximum when the energy levels of the two wires are aligned such that the Fermi velocities (or electron densities) in the wires are nearly equal. If the alignment is perfect, the drag should decrease linearly with temperature; otherwise the decrease is found to be exponential (see equation (2) below). Further theoretical work concentrated on the drag between 1D systems in the presence of disorder [7] or in the ballistic regime [8, 9]. The common feature of the papers cited above is that they are based on the Fermi liquid (FL) description of the 1D electron systems, where the excitations are viewed as well-defined Fermi quasiparticles.

On the other hand, it is expected that in the 1D case the Coulomb interaction between electrons modifies both the ground state and the elementary excitations of the electron systems in such a way that the systems should be described in terms of a Tomonaga–Luttinger (TL) liquid rather than in terms of a FL model [10]. In recent theoretical papers [11–14] the Coulomb drag between 1D systems has been studied within the TL liquid concept. The main result of the studies [11–13] is that the interwire momentum transfer is modified by electron–electron interactions in such a way that the drag is enhanced at low temperatures, until at $T = 0$, interlocked charge-density waves form in the wires and the drag resistance diverges. A simple qualitative explanation of this phenomenon is based on the observation that the drag results from backscattering of density excitations in one wire from density fluctuations in the other. Therefore, the situation is similar to that of a TL liquid with backscattering at an impurity and it is known [15] that for repulsive interaction the effective backscattering strength increases with decreasing temperature and eventually diverges at $T = 0$. The strong-coupling regime, when the drag resistance diverges, may remain elusive experimentally since in the wires of finite length at sufficiently low temperatures the drag becomes suppressed due to the influence of the Fermi liquid reservoirs to which the wires are connected [14]. Nevertheless, the predicted increase of the drag with decreasing temperature in a characteristic power-law fashion [13] is in sharp contrast with the prediction of FL theories and, therefore, may serve as a signature of the TL behaviour. To stress the importance of this suggestion, we notice that the TL behaviour does not manifest itself in simpler experiments, where single-wire conductance is investigated: the measured conductance remains independent of the Coulomb interaction [16] because of the influence of the reservoirs and of the screening effects.

Though a fair amount of theoretical work is available on the CD between 1D electron systems, there has been a conspicuous absence of experimental work on the subject. Recently, we have briefly reported [17] experimental evidence of CD between ballistic quantum wires. The present work consists of more extensive studies and reports results on the temperature, interwire distance, driving voltage, and magnetic field dependencies of the drag resistance R_D. The most important observation is that in the temperature region $0.2 \text{ K} \leqslant T \leqslant 1 \text{ K}$ R_D increases with decreasing temperature as $R_D \propto T^x$, where x ranges from -0.6 to -0.77 depending on the Fermi level position with respect to the 1D subbands. The observed features of the temperature dependence of R_D can be successfully explained in the framework of the TL liquid theory.

The paper is organized as follows. In section 2 we describe the samples and the measurement techniques used. The experimental results obtained are summarized in section 3. Analysis of the results and a discussion follow in section 4.

2. Device and experimental techniques

The quantum-wire samples were fabricated from a two-dimensional electron gas (2DEG) located 80 nm below the surface at the interface of a MBE-grown Si modulation-doped AlGaAs/GaAs heterostructure. At 4.2 K, the 2DEG had an electron concentration of 2.7×10^{15} m^{-2} and a mobility of 70 m^2 V^{-1} s^{-1}, giving a Fermi energy of 9.7 meV and an electron mean free path of 6 μm. The experimental device was a planar structure consisting of three independent surface Schottky gates: top gate T, middle gate M of 50 nm width, and bottom gate B. The three gates form two lithographically defined constrictions of width 250 nm and length $L = 2$ μm (figure 1). The device was mounted on the mixing chamber of a dilution cryostat and thermally bonded to it. By negative voltage biasing of the gates T, M, and B that depletes the 2DEG under them, two electrically isolated conduction channels could be created. The central parts of these channels form two quantum wires of 2 μm nominal length. The conduction channels widen out at both ends forming 2D reservoirs which ensure phase randomizing. The geometrical shapes of the gate edges were designed to ensure adiabatic transition from wide to narrow regions. By appropriate voltage biasing of the gates T, M, and B, it was possible to vary the width and separation of the quantum wires. Electrical characterization of the wires was carried out by measuring their conductance at 60 mK using a standard low-bias, low-frequency, lock-in technique. The conductance was measured, of one wire at a time, and of both simultaneously, as a function of wire width by varying the appropriate gate voltages to establish the ballistic nature of the electron transport and to check whether the two wires showed identical transport behaviour. The two wires were found to have nearly identical conductance staircases with a small difference in the pinch-off voltages which could be compensated for by introducing an adequate voltage shift between the gates T and B. The measured conductance showed characteristic features of ballistic transport (figure 2). However, the observed conductance plateaus were not sufficiently well defined due, very likely, to deviations from adiabaticity at the constriction openings and scattering in the wires caused by roughness of the gate edges. The application of a magnetic field B perpendicular to the plane of the device improved the adiabaticity and reduced the scattering, producing fairly well-defined conductance plateaus at $B \simeq 1$ T (figure 2). On the other hand, we did not see either sharp peaks in the pinch-off regime or dips superimposed on the first plateau, like for wires with strong disorder [18]. This allowed us to conclude that a true 1D transport regime has been realized in our experiment. The information obtained from the above characterization made it

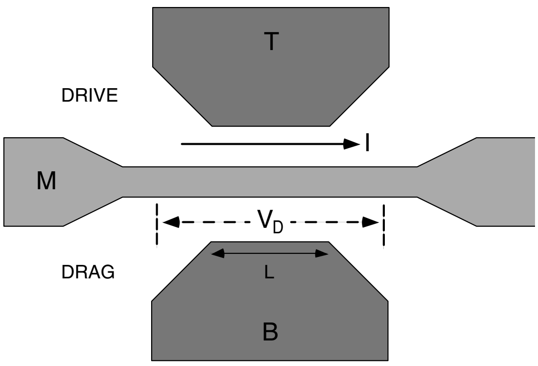

Figure 1. A schematic diagram of a quantum-wire device used for the Coulomb-drag measurements.

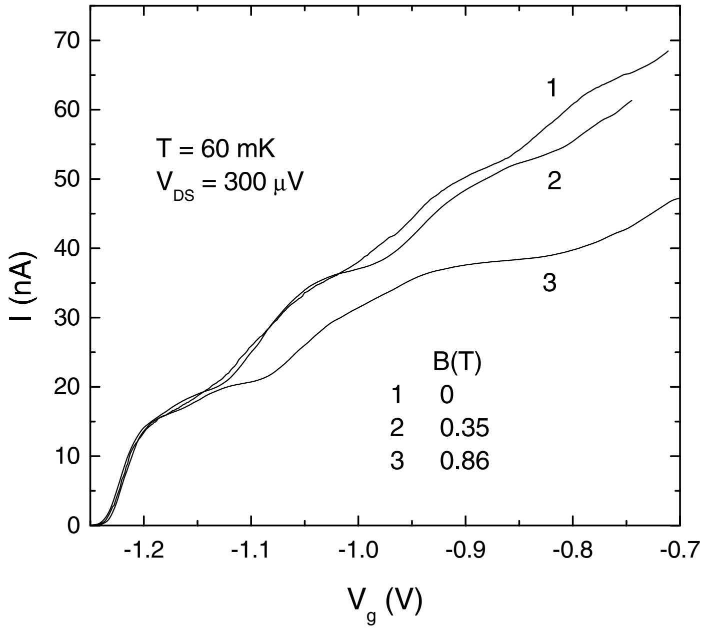

Figure 2. The conductance staircase of the top wire as a function of the bias voltage V_g applied to the gates T and M with gate B grounded at 60 mK and in different magnetic fields: 0 (1), 0.35 (2), and 0.86 T (3). Similar results were obtained for the bottom wire except for a small difference in the pinch-off voltage.

possible to choose later, by adjusting the appropriate gate voltages, the location of the Fermi level E_F in a specific 1D subband and/or the relative alignment of the 1D subbands belonging to the two wires. For measurements of the CD the top wire was chosen as the drive wire and the bottom one as the drag wire. Measurements were carried out on a number of devices and the results presented in section 3 are representative of typical device behaviour.

3. Experimental results

To be sure that the measurements of the drag effect were made in the absence of interwire tunnelling, we first measured the tunnelling current across the middle gate between the drain of the drive wire and the source of the drag wire. The results shown in figure 3 indicate that for typical values of the top and bottom gate voltages used the tunnelling current could be neglected for middle gate voltage $V_M < -0.7$ V. For all subsequent drag measurements, V_M was chosen to be less than -0.7 V, except for studying the dependence of the drag on the interwire separation when higher values were used.

To carry out measurements of the drag voltage V_D, first the middle gate voltage V_M and the bottom gate voltage V_B were chosen to have E_F slightly above the bottom of the lowest 1D subband of the drag wire. A drive bias voltage V_{DS}, low enough to be within the linear regime of transport, was applied to the drive wire to send a current I through it. No current was allowed to flow in the drag wire. V_D and I were then measured simultaneously as the voltage V_T of the top gate was swept. Measurements were done at 70 mK in the absence of any applied magnetic field. In figure 4 we show the measured drag voltage V_D as a function of V_T for fixed values of V_M and V_B as given in the figure caption. The drag voltage shows

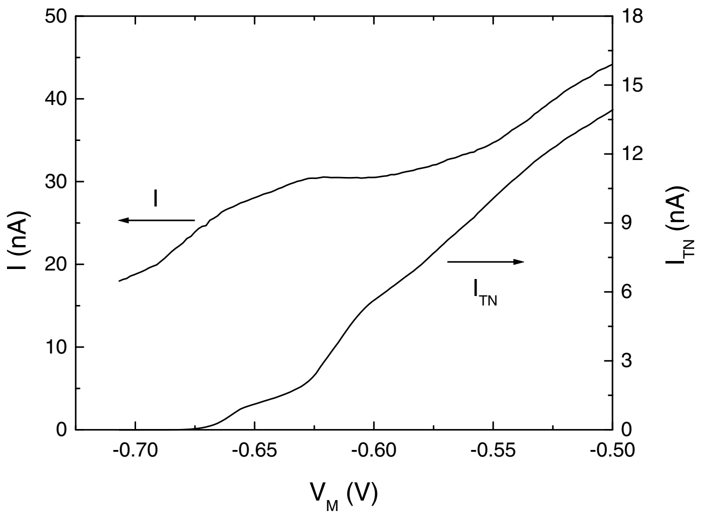

Figure 3. Interwire tunnelling current I_{TN} as a function of the middle gate voltage V_M at 60 mK and in zero magnetic field. I is the drive current in the top wire. $V_B = -1.5$ V, $V_T = -1.2$ V, and $V_{DS} = 300$ μV. Note that the above values of V_B and V_T are approximately those at which a maximum drag effect is observed in later measurements with $V_M = -0.74$ V.

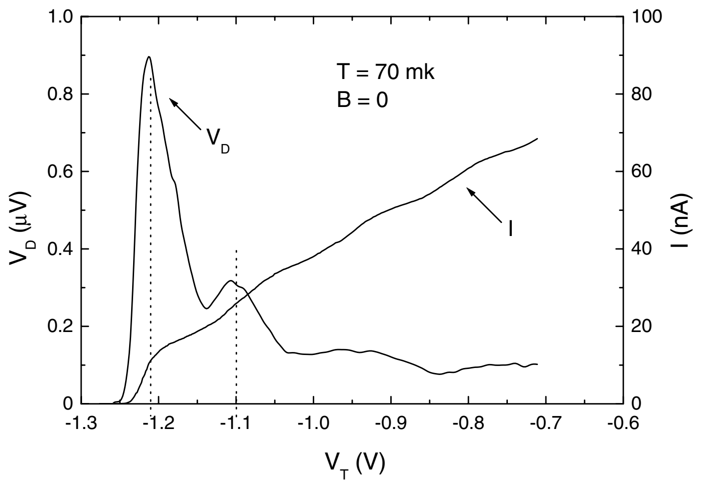

Figure 4. Drag voltage V_D and drive current I as functions of the top gate voltage V_T at 70 mK and in zero magnetic field with a drive voltage of 300 μV. $V_M = -0.74$ V, $V_B = -1.525$ V. For these values of V_M and V_B the Fermi level E_F is located just above the bottom of the lowest 1D subband of the drag wire.

two prominent peaks, a strong one at $V_T = -1.21$ V and a weaker one at $V_T = -1.10$ V. The peaks are found to occur in the rising parts (steps) between the conductance plateaus of the drive wire. This suggests that they occur when the bottom of the second and the first 1D subband of the drive wire align themselves, one after another, with the bottom of the lowest 1D subband of the drag wire as V_T is varied.

Figure 5 shows the dependence of V_D^{MAX}, the height of the first V_D-peak of figure 4, on the drive bias voltage V_{DS} in zero magnetic field at 60 mK. Except for the temperature, the

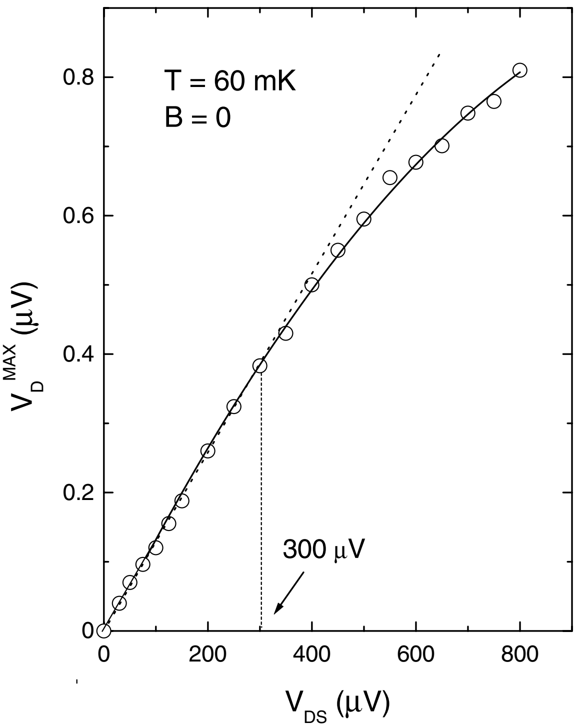

Figure 5. The maximum V_D^{MAX} of the first drag voltage peak of figure 4 as a function of the drive voltage V_{DS} at 60 mK in zero magnetic field. The linear regime is maintained for V_{DS} at least up to 300 μV.

measurement procedure and the experimental conditions were the same as those for figure 4. V_D^{MAX} is found to vary linearly with V_{DS} up to about 350 μV indicating linear transport in this range of V_{DS}. The dependence becomes sublinear beyond this value. The results of figure 5 demonstrate that the measurements of figure 4 carried out with $V_{DS} = 300$ μV lie well within the linear transport regime. The observation of this linear behaviour for $eV_{DS} \gg k_B T$, though surprising, can be understood when one considers the inhomogeneity of the width of the quantum wires along the length due to the roughness of the gate edges (section 4).

Since a magnetic field applied perpendicular to the plane of the device improved the quality of the conductance staircase (figure 2), measurements of V_D were also carried out in a field to study its influence on the CD. In figure 6 we show the results for zero field and in a field $B = 0.86$ T at 70 mK. Two clear effects of the field are observed. First, V_D^{MAX} for the first drag peak is enhanced almost by a factor of 3. Second, there is a narrowing of this peak. In addition, a weakening of the second drag peak is observed under the influence of magnetic field. V_D is also found to remain linear in V_{DS} (figure 7) at least up to 300 μV. As shown in the figure, the linear behaviour is valid not only for the peak height, but also for the entire peak region.

The CD effect is expected to decrease [8, 9] strongly as the interwire separation d increases. In the voltage range of interest, d is found to vary almost linearly with V_M according to

$$d = d_0 + \alpha(V_0 - V_M) \qquad (1)$$

where V_0 is the value of V_M for which the 2DEG under the middle gate M is just depleted and α gives the total spatial displacement of the two depletion edges of M with respect to its bias

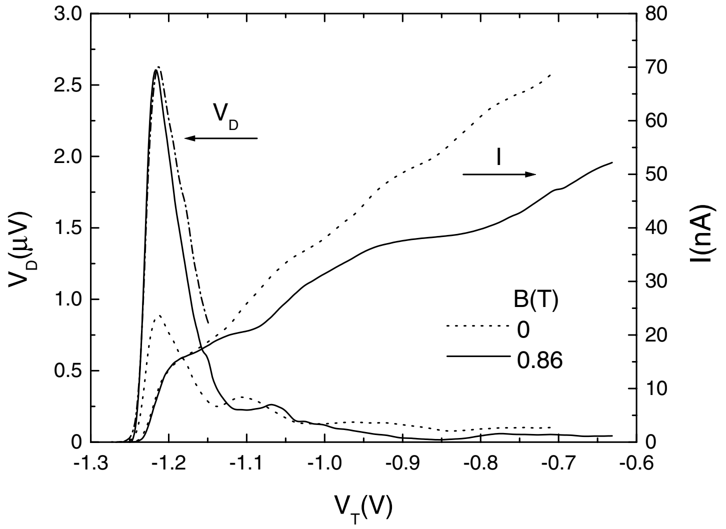

Figure 6. Drag voltage V_D and drive current I as functions of the top gate voltage V_T at 70 mK in zero field and in a magnetic field of 0.86 T with $V_{DS} = 300\ \mu$V. $V_M = -0.74$ V and $V_B = -1.51$ V. The dot–dash peak is the zero-field result with its peak height normalized to that of the peak in 0.86 T. The field enhances V_D almost by a factor of 3 and narrows the drag peak.

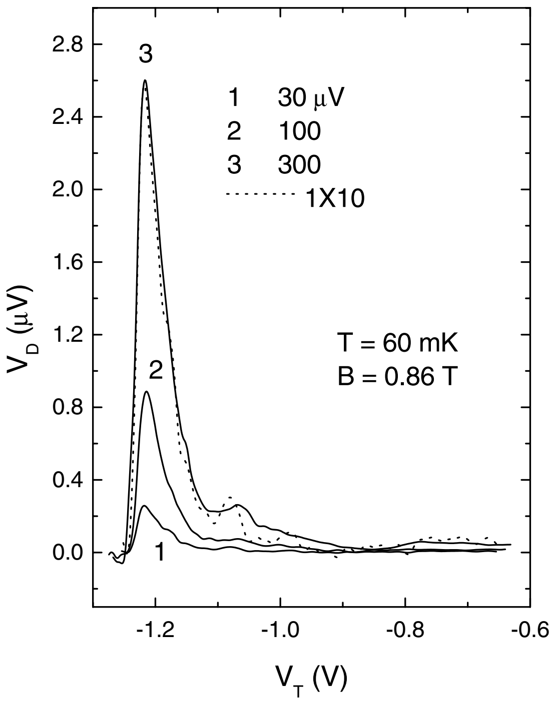

Figure 7. Drag voltage V_D as a function of the top gate voltage V_T for three values of the drive voltage V_{DS} at 60 mK in a magnetic field of 0.86 T: 30 (1), 100 (2), and 300 μV (3). $V_M = -0.74$ V and $V_B = -1.508$ V. The dotted peak is the one for 30 μV magnified by a factor 10 and shows complete linearity of V_D with V_{DS} up to at least 300 μV.

voltage. Note that d_0 is a constant for the same device and is nominally equal to the lithographic width of the gate M which is 50 nm in our devices. We determined V_0 by measuring the 2D–1D transition of the conductance of our devices. To do this, the conductance of the device was measured as a function of bias voltage applied simultaneously to gates M and T or B, while the third gate was grounded. A sharp drop in the conductance occurs at V_0 when the 2DEG under the two gates is depleted and a quantum wire is created. V_0 was found to be -0.4 V. The coefficient $\alpha = 580$ nm V^{-1} was determined from the measured conductance staircases of the quantum wires, making use of the experimental value of the Fermi energy. Figure 8(a) shows how V_D^{MAX} for the first drag peak depends on V_M at 60 mK. To carry out these measurements, each time V_M was changed, V_B was adjusted to maintain the same width of the drag wire so that E_F was always just above the bottom of the lowest 1D subband. V_D was then measured as a function of V_T. Measurements were done in a field of $B = 0.86$ T to make use of the enhanced drag effect in a field. V_D^{MAX} is found to increase as V_M becomes less negative due to a decrease in d in accordance with equation (1). It reaches a maximum value at $V_M \simeq -0.69$ V, then decreases again for $V_M > -0.69$ V when interwire tunnelling occurs (figure 3). The dependence of the corresponding drag resistance on V_M in the absence of interwire tunnelling is found to be exponential and can be described well by the relation $R_D \propto e^{\beta V_M}$, where $\beta \simeq 14.2(9)$ V^{-1}. This is illustrated in figure 8(b).

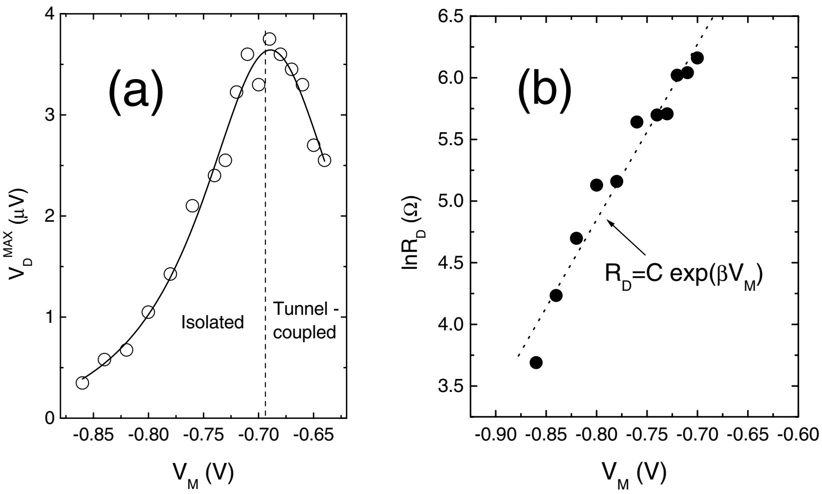

Figure 8. The dependence of the drag response on the interwire separation. (a) The maximum V_D^{MAX} of the first drag peak of figure 6, in a magnetic field, as a function of the middle gate voltage V_M at 60 mK. (b) The natural logarithm of the corresponding drag resistance R_D as a function of V_M. The dotted line is a linear fit to the data points.

As mentioned in section 1, the temperature dependence of the CD effect is a crucial feature that can be used to probe which one of the two theoretical models, the FL or TL liquid, constitutes a more appropriate description of the 1D CD effect. With this in mind, we measured V_D as a function of the temperature T with T in the range from 60 mK to 1.2 K, both in zero magnetic field and in a field $B = 0.86$ T. Since the effect is enhanced in a magnetic field, a drive bias voltage of 50 μV was used in its presence. Except for the temperature, the experimental conditions and the measurement procedure were the same as those used for obtaining the results of figures 4 and 6. The results are shown in figures 9(a) and 9(b). A decrease of V_D with increasing temperature is observed. The dependence on temperature of the drag resistance R_D corresponding to the maximum of the first drag peak is shown in figures 10(a) and 10(b).

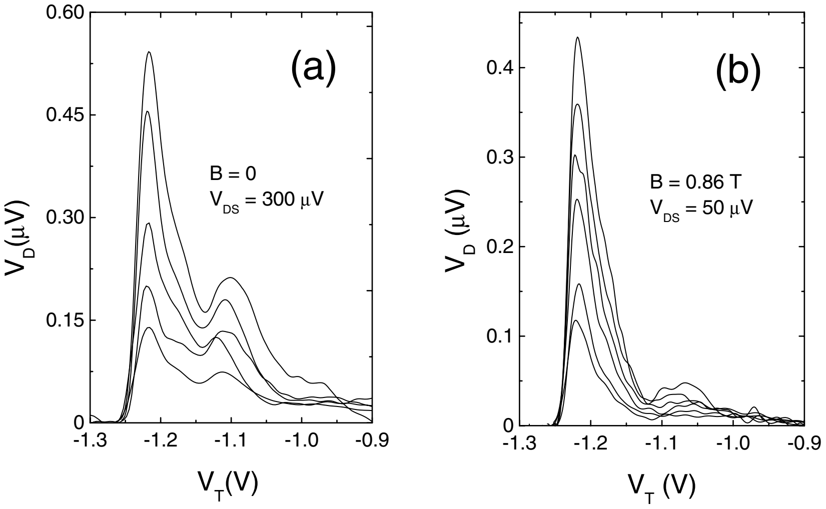

Figure 9. The dependence of the drag response on the temperature. (a) The drag voltage V_D as a function of the top gate voltage V_T in zero magnetic field with 300 μV drive voltage at temperatures 70, 180, 300, 450, and 900 mK, corresponding to the curves in the order of decreasing peak height. (b) The same as in (a) but in a magnetic field of 0.86 T and with a $V_{DS} = 50\ \mu$V at temperatures 60, 180, 300, 450, 900 mK and 1.2 K. For both (a) and (b), $V_M = -0.74$ V and $V_B = -1.508$ V.

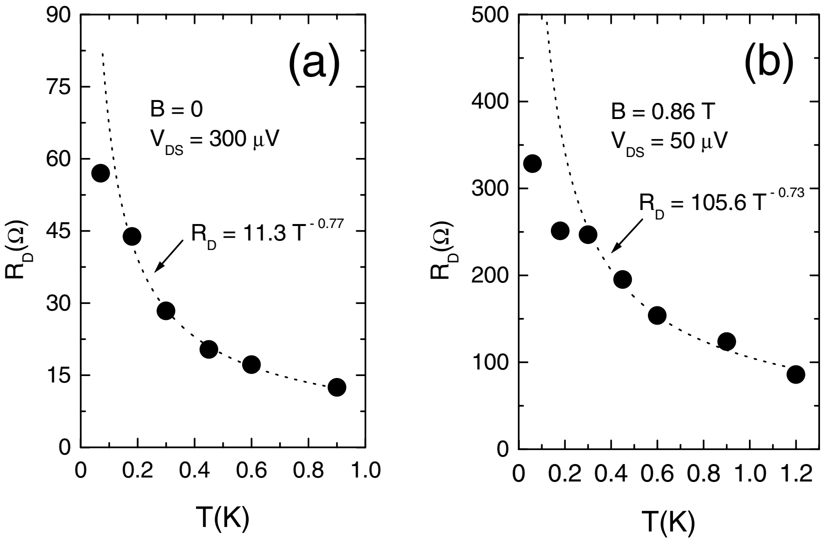

Figure 10. The temperature dependence of the drag resistance R_D corresponding to V_D^{MAX} for the first drag peak of figure 9 in zero field (a) and in a magnetic field of 0.86 T (b). Note that the data points at the low end of the temperature range fall below the power-law curve indicating a suppression of the drag effect at these temperatures.

In the range $0.2\ \text{K} \leqslant T \leqslant 1.2$ K, the temperature dependence of R_D can be described well by the power law $R_D \propto T^x$ with $x = -0.77(2)$ and $-0.73(6)$ for $B = 0$ and $B = 0.86$ T, respectively. It is interesting to note that the data points at temperatures lower than 180 mK, for zero field, and than 300 mK, for nonzero field, fall below the power-law curve, indicating a suppression of the drag effect. As we move to the right shoulder of the drag peak, toward less negative V_T, the temperature dependence of R_D becomes progressively weaker but also fits well to power laws. For example, at $V_T = -1.17$ V we found $x = -0.61(2)$.

4. Discussion

The origin of the observed peaks in V_D (figure 4) can be understood when one considers a simple equation [8] for the drag resistance between quantum wires derived in the FL framework for zero magnetic field:

$$R_D = \frac{Lk_B T|\bar{V}_{k_{F1}+k_{F2}}|^2}{\hbar^2 e^2 v_{F1} v_{F2}(v_{F1} + v_{F2})} \frac{(\Delta/2k_B T)^2}{\sinh^2(\Delta/2k_B T)}. \tag{2}$$

Here Δ is the difference between the quantization energies of the 1D states in the two wires, L the wire length, while k_{Fi} and $v_{Fi} = \hbar k_{Fi}/m^*$ are the Fermi wave vectors and Fermi velocities in the wire i ($i = 1, 2$). Next, $\bar{V}_q$ is the interwire matrix element of the Coulomb potential, which can be approximated by $(2e^2/\epsilon)K_0(qd)$, where K_0 is the modified Bessel function, d the interwire distance, and ϵ the dielectric constant. According to equation (2), the magnitude of the CD effect is proportional to the backscattering probability due to the Coulomb interaction between the Fermi quasiparticles of different wires. The drag is enhanced when the 1D levels of the two wires are aligned, which corresponds to $\Delta = 0$ and $k_{F1} = k_{F2} = k_F$, and the Fermi wave vectors in the wires are small so the interwire momentum transfer $\hbar q = \hbar(k_{F1} + k_{F2}) = 2\hbar k_F$ is also small. As seen from figure 4, the occurrences of the drag peaks correspond to these conditions. The first peak in V_D occurs when the Fermi level is just above the bottoms of the lowest 1D subbands of both wires. Similarly, the second peak occurs when the lowest subband of the drag wire lines up with the second subband of the drive wire [9, 17]. Both the increase and the narrowing of the first drag peak in a magnetic field of 0.86 T (figure 6) can be attributed to an increase of the density of states in 1D subbands due to the magnetic-field-induced enhancement of the effective mass. The theoretical calculations [9] of the influence of a magnetic field on the CD between quantum wires show the same tendencies (see figure 2 of [9]). The theory also suggests a suppression of the drag due to a reduction of the backscattering probability as the centres of the wave functions of forward- and backward-moving electrons are pulled apart by the magnetic field [9]. Since the magnetic length for 0.86 T field is 28 nm and the effective width of the drive wire for the first subband is about 23 nm, this effect should not have a very considerable influence on the first drag peak. However, because of the larger effective wire width, the field-induced shift of the wave functions is expected to be significant for the second subband. This can explain the observed decrease of the amplitude of the second peak in the magnetic field. Since we are mainly concerned with 1D transport in the fundamental mode, hereafter we discuss only the region of the first drag peak.

To estimate the interwire distance dependence of the drag effect at large d, one may use the asymptotic form of the Bessel function in the expression for R_D. Since $R_D \propto [K_0(2k_F d)]^2$ and $K_0(2k_F d)$ behaves as an exponential for $2k_F d \gg 1$, we expect an exponential decrease of R_D with d:

$$R_D \propto \mathrm{e}^{-4k_F d}. \tag{3}$$

Experimentally, the effective separation between the wires is found to be proportional to the middle gate voltage, which moves the depletion edges in a nearly linear way and thus changes d (equation (1)). The observed exponential dependence (figure 8(b)) of $R_D \sim \mathrm{e}^{\beta V_M} \sim \mathrm{e}^{-\gamma d}$ with $\gamma = \beta/\alpha$ is therefore consistent with equation (3) and can be used to estimate the Fermi wave vector corresponding to the peak value of V_D. Using the experimentally determined values $\beta \simeq 14.2\ \mathrm{V}^{-1}$ and $\alpha \simeq 580\ \mathrm{nm\ V}^{-1}$, we find $k_F \simeq 6.1 \times 10^6\ \mathrm{m}^{-1}$. When V_M is in the range from −0.7 to −0.8 V, we have[1] $d \simeq 0.2\ \mu$m. This gives $2k_F d \sim 3$, so the approximation of equation (3) is still reasonable.

The features discussed above, namely the origin of the peaks, the magnetic field effect, and the interwire separation dependence, can all be understood in terms of the FL theory of CD between ballistic 1D electron systems. We now discuss the features which cannot be explained in this framework. The observed temperature dependence of the drag resistance shown in figures 10(a) and 10(b) is in sharp contrast with the *linear* behaviour $R_D \sim T$ expected for Fermi liquids; see equation (2) for $\Delta \to 0$. The unusual temperature dependence cannot be attributed to a temperature-induced modification of the wire conductance, since the latter is found to be almost unchanged in this range of temperatures. A reduction of the interwire Coulomb coupling due to enhanced screening by the reservoirs and gates is very unlikely at such small temperatures. On the other hand, it is conceivable that correlated liquid behaviour is established in the wires. Indeed, it is hardly surprising that the temperature dependence of the observed CD does not fit into the FL scenario, because for the peak conditions the ratio of the mean distance between the electrons in the same wire to the Bohr radius $\bar{r}/a_B \simeq 26$ is large. Below we find that the temperature dependence of R_D is in good agreement with a theory [13] of the CD between TL liquids.

The essential point of the TL liquid theory of Coulomb drag is that the interwire Coulomb-assisted backscattering probability λ, which determines the drag resistance R_D, is affected by the intrawire Coulomb interaction and becomes temperature dependent, $\lambda = \lambda(T)$, in contrast to the bare probability λ_0. The smallness of the observed drag resistance ($R_D < 100\ \Omega$; figure 10(a)) in comparison with the fundamental resistance $h/2e^2$ indicates a weak interwire coupling. According to [13], in this case $\lambda(T)$ should scale with temperature in a power law, $\lambda(T) \propto T^{2K_{c-}-2}$, provided that the 1D levels in the wires are aligned. The exponent is expressed through the TL parameter K_{c-} of the relative (i.e., interwire) charge mode. Therefore, instead of the linear temperature dependence $R_D \propto \lambda_0 T$, typical for the case when the intrawire Coulomb interaction is either neglected or treated in a perturbative approach within the FL framework [8], one gets

$$R_D \propto \lambda(T)T \propto T^x \qquad x = 2K_{c-} - 1. \tag{4}$$

The power-law behaviour is indeed observed in our experiment; cf. figure 10(a). Assuming that equation (4) is applicable, one can determine the parameter K_{c-} from the experimental data. We find $K_{c-} = 0.12$–0.2, depending on the gate voltage V_T. It is crucial, however, to check whether the rather low values of K_{c-} obtained are realistic and consistent with the system parameters.

A recent work by Creffield *et al* [19] demonstrates that the interaction parameter of a single quantum wire calculated by standard perturbative methods yields reliable values, even for small values of $k_F w$ (w is the width of the wire) down to 0.1, while in our experiment $w \simeq 23$ nm (determined from experimental data) and $k_F w \simeq 0.14$. Encouraged by this result, we determine K_{c-} in a similar way via the compressibility of the relative charge mode obtained in the Hartree–Fock approximation, which leads to

$$K_{c-}^{HF} = \left(1 + \frac{2(V_0 - \bar{V}_0)}{\pi v_F} - \frac{V_{2k_F}}{\pi v_F}\right)^{-1/2} \tag{5}$$

[1] The estimated value of d was obtained by two independent methods. The first method used experimental data on gate-edge depletion (see section 3 for details) while the second one was based upon electrostatic calculations of the double-well potential profile created by three parallel infinite gates for $V_M = -0.8$ V and $V_T = V_B = -1.5$ V (the variations of the gate voltages within the ±0.05 V range do not change this estimate considerably). Both methods give values of d close to 0.2 μm, which is chosen for numerical estimates in section 4.

where V_q and $\bar{V}_q$ denote intra- and interwire matrix elements of the Coulomb potential, respectively. Modelling them as one-dimensional Fourier transforms of the potentials

$$V(x) = e^2\epsilon^{-1}(x^2 + w^2)^{-1/2} \qquad \bar{V}(x) = e^2\epsilon^{-1}(x^2 + d^2)^{-1/2}$$

we obtain an interaction parameter $K_{c-}^{HF} = 0.178$. This calculation is done for parameters $d = 0.2\ \mu$m, $w = 23$ nm, $k_F = 6.1\ \mu\text{m}^{-1}$, $\epsilon = 12.5$, and $m^* = 0.068\ m_e$. If we take into account screening by a homogeneous gate, i.e., subtract the image charge potentials

$$e^2\epsilon^{-1}(x^2 + w^2 + 4l^2)^{-1/2} \qquad e^2\epsilon^{-1}(x^2 + d^2 + 4l^2)^{-1/2}$$

($l = 80$ nm), from $V(x)$ and $\bar{V}(x)$, respectively, we obtain $K_{c-}^{HF(S)} = 0.212$. Since we have split gates, the true value of K_{c-} lies somewhere between K_{c-}^{HF} and $K_{c-}^{HF(S)}$ and is in reasonable agreement with the experimental values. Since the distance between the wires in our experiment is larger than the thickness of the layer between the 2DEG and the surface Schottky gates, the screening by the gates appears to be important. Nevertheless, our analysis of the experimental data based on the exponential dependence given by equation (3) remains valid irrespective of whether the screening is present or not. To demonstrate this, we stress that both in the FL and in the TL liquid framework the drag resistance is proportional to the square $|\bar{V}_{2k_F}|^2$ of the $2k_F$-component of the interwire interaction, which leads to equation (3) under the condition $d > k_F^{-1}$.

Strictly speaking, the result (4) is valid for infinitely long wires. The temperature dependence should be modified if the wire length L is smaller than the thermal length L_T estimated as $L_T = \hbar v_F / K_{c-} k_B T$. The length L_T has a simple physical meaning: since v_F/K_{c-} is the group velocity of the relative electron-density fluctuations, and $\hbar/k_B T$ is the quantum lifetime associated with the thermal energy $k_B T$, the length L_T is the quantum wavelength associated with this energy. The electron coming from the lead to the wire does not have time to accommodate itself to the TL liquid if $L < L_T$, so in this case the drag effect should be weaker than that following from equation (4). Given a Fermi wave vector of $k_F \simeq 6\ \mu\text{m}^{-1}$, we find that L_T exceeds $L = 2\ \mu$m for temperatures below $T_L \simeq 250$ mK. At higher temperatures equation (4) should be applicable. The experimental data are consistent with these estimates. At lower temperatures we do indeed observe a tendency to a weakening of the drag with respect to the power-law dependence; cf. figure 10(a).

The influence of the magnetic field on the temperature dependence is not significant, as follows from a comparison of figures 10(a) and 10(b). This may signify that Zeeman spin splitting at $B \leqslant 1$ T is not important yet (otherwise, for spin-polarized electrons, the exponent x should change [13]). Indeed, we do not see signatures of spin splitting in the quantized conductance staircase in this field (figure 2). Another effect of the magnetic field is a decrease of the parameter V_{2k_F} related to intrawire backscattering. As the wave functions for the left- and right-moving electrons are pulled apart by the magnetic field, this parameter is expected to decrease rapidly. This, however, cannot affect the temperature dependence considerably, since this parameter is small in comparison with parameters V_0 and $\bar{V}_0$—see equation (5)—which are less affected by the field. The magnetic field also increases v_F for the same position of the Fermi level. As long as this effect is small, this cannot produce a significant change of the temperature dependence determined by parameter K_{c-}. Note, however, that the increase of v_F makes the thermal length L_T bigger at the same temperature. This can explain why a deviation from the power-law dependence occurs at a higher temperature, as seen from figure 10(b).

The negative power-law temperature dependence is not the only experimental feature that cannot be explained in the FL theory of the CD. It is worth mentioning that the experimental value of R_D (figure 10(a)) at $T = 60$ mK is more than one order of magnitude larger than that resulting from equation (2). That the measured drag is larger could be explained by the interaction-renormalized interwire backscattering probability, which should be larger than the bare one.

The experimental data at $T = 60$ mK show that V_D still remains linear in the driving voltage up to 350 μV (figure 5) though it is expected to show nonlinear behaviour starting from $V_{DS} = (k_B/e)T \sim 6$ μV. This estimate, however, corresponds to ideal ballistic wires, while in the real wires the inhomogeneities of the conducting channels, appearing mostly due to the roughness of the gate edge, should lead to a smearing of the band edges, extending the region of linearity. This disorder smearing is also seen in the quantized conductance staircase (figure 2), and we conclude that at $T = 60$ mK it is much more important than the thermal smearing of the Fermi distribution. Besides, within the TL liquid description of transport, the extended linearity region can be in part attributed to a considerable reduction of the electric field inside the wire due to the renormalization of the group velocity of the excitations as a result of the interactions [20]. If $K_{c-} = 0.2$, this corresponds to an increase of the linearity region by a factor of 5, which, however, is not sufficient to explain the experimental data without consideration of disorder smearing. More surprising is the sublinear behaviour of V_D for $V_{DS} > 350$ μV. The FL theory of the CD predicts a superlinear behaviour [21] $R_D \sim V_{DS}^2$ for $eV_{DS} \gg k_B T$ and $eV_{DS} \gg \Delta$. This behaviour is qualitatively understandable, since the phase space for electron transition in electron–electron scattering increases with the increasing drive voltage. The experimentally observed sublinear behaviour contradicts this picture, and, therefore, cannot be explained using the FL theory. On the other hand, very probably it could be explained in the TL liquid framework, because the effect of increasing the drive voltage is similar to that of increasing the temperature described above: in both cases the electron–electron correlation is expected to weaken. Unfortunately, we cannot present here quantitative arguments supporting this suggestion, since the nonlinear drag between TL liquids has not yet been studied theoretically.

So far we have interpreted our experimental results in terms of Coulomb drag only. However, considering the large interwire separation in our experiment, one cannot completely rule out the possibility of an acoustic phonon-mediated drag (PMD) contribution to the drag resistance. Because there is no information available on PMD in 1D systems, we cannot give a detailed analysis of this question. Nevertheless, existing results for 2D systems [22] show that the PMD rapidly decreases with temperature T at $T < 2$ K and does not decrease exponentially with increasing interlayer separation. Our data on the temperature and interlayer separation dependence of R_D qualitatively contradict this behaviour. This allows us to conclude that the PMD contribution, if present at all, is insignificant in our experiments.

In conclusion, we have investigated the Coulomb drag between ballistic 1D electron systems and studied its dependence on interwire separation and temperature in the absence of tunnelling between the wires. The observed negative power-law temperature dependence of the drag resistance can be explained quantitatively in terms of the TL liquid theory. The observed sublinear dependence of the drag voltage on the drive voltage also seems to be consistent with the TL liquid description of electron transport. Thus, we have good indications that the electron systems in the wires investigated are Tomonaga–Luttinger liquids. Clearly, further experimental and theoretical work is necessary to put the TL nature of Coulomb drag on a firm footing.

Acknowledgments

The authors are grateful to A Stern and V L Gurevich for fruitful discussions. PV acknowledges support from the NSERC Grant No OGP0121756.

References

[1] Gramila T G, Eisenstein J P, MacDonald A H, Pfeiffer L N and West K W 1991 *Phys. Rev. Lett.* **66** 1216
[2] For a recent review see Rojo A 1999 *J. Phys.: Condens. Matter* **11** R31
[3] Lilly M P, Eisenstein J P, Pfeiffer L N and West K W 1998 *Phys. Rev. Lett.* **80** 1714
[4] Feng X G, Zelakiewicz S, Noh H, Ragucci T J, Gramila T G, Pfeiffer L N and West K W 1998 *Phys. Rev. Lett.* **81** 3219
[5] Sirenko Yu M and Vasilopoulos P 1992 *Phys. Rev.* B **46** 1611
Tso H C and Vasilopoulos P 1992 *Phys. Rev.* B **45** 1333
[6] Hu B Y-K and Flensberg K 1996 *Hot Carriers in Semiconductors* ed K Hess *et al* (New York: Plenum) p 261
[7] Tanatar B 1998 *Phys. Rev.* B **58** 1154
[8] Gurevich V L, Pevzner V B and Fenton E W 1998 *J. Phys.: Condens. Matter* **10** 2551
[9] Raichev O E and Vasilopoulos P 2000 *Phys. Rev.* B **61** 7511
[10] Voit J 1994 *Rep. Prog. Phys.* **57** 977
[11] Flensberg K 1998 *Phys. Rev. Lett.* **81** 184
[12] Nazarov Yu A and Averin D V 1998 *Phys. Rev. Lett.* **81** 653
[13] Klesse R and Stern A 2001 *Phys. Rev.* B **62** at press
[14] Ponomarenko V V and Averin D V 2001 *Phys. Rev. Lett.* **85** at press
[15] Kane C L and Fisher M P A 1992 *Phys. Rev. Lett.* **68** 1220
Kane C L and Fisher M P A 1992 *Phys. Rev.* B **46** 15 233
[16] Safi I and Schulz H J 1995 *Phys. Rev.* B **52** R17 040
Safi I 1997 *Phys. Rev.* B **55** R7331
Ponomarenko V V 1995 *Phys. Rev.* B **52** R8666
Oreg Yu and Finkel'stein A M 1996 *Phys. Rev.* B **54** R14 265
Kawabata A 1996 *J. Phys. Soc. Japan* **65** 30
Shimizu A 1996 *J. Phys. Soc. Japan* **65** 1162
[17] Debray P, Vasilopoulos P, Raichev O, Perrin R, Rahman M and Mitchel W C 2000 *Physica* E **6** 694
[18] Auslaender O M, Yacoby A, de Picciotto R, Baldwin K W, Pfeiffer L N and West K W 2000 *Phys. Rev. Lett.* **84** 1764
[19] Creffield C E, Häusler W and MacDonald A H 2000 *Preprint* cond-mat/0005354
[20] Sablikov V A and Shchamkhalova B S 1998 *Phys. Rev.* B **58** 13 847
[21] Gurevich V L and Muradov M I 2000 *JETP Lett.* **71** 111
[22] Tso H C, Vasilopoulos P and Peeters F M 1992 *Phys. Rev. Lett.* **68** 2516
Gramila T G, Eisenstein J P, MacDonald A H, Pfeiffer L N and West K W 1993 *Phys. Rev.* B **47** 12 957
Bonsager M C, Flensberg K, Hu B Y-K and MacDonald A H 1998 *Phys. Rev.* B **57** 7085
Badalyan S M and Rössler U 1999 *Phys. Rev.* B **59** 5643
Noh H, Zelakiewicz S, Gramila T J, Pfeiffer L N and West K W 1999 *Phys. Rev.* B **59** 13 114