Positive and negative Coulomb drag in vertically integrated one-dimensional quantum wires

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Electron interactions in and between wires become increasingly complex and important as circuits are scaled to nanometre sizes, or use reduced-dimensional conductors such as carbon nanotubes2–4, nanowires7–10 and gated high-mobility two-dimensional electron systems11–13. This is because the screening of the long-range Coulomb potential of individual carriers is weakened in these systems, which can lead to phenomena such as Coulomb drag, where a current in one wire induces a voltage in a second wire through Coulomb interactions alone. Previous experiments have demonstrated Coulomb electron drag in wires separated by a soft electrostatic barrier of width $\lesssim 80$ nm (ref. 12), which was interpreted as resulting entirely from momentum transfer. Here, we measure both positive and negative drag between adjacent vertical quantum wires that are separated by $\sim 15$ nm and have independent contacts, which allows their electron densities to be tuned independently. We map out the drag signal versus the number of electron sub-bands occupied in each wire, and interpret the results both in terms of momentum-transfer and charge-fluctuation induced transport models. For wires of significantly different sub-band occupancies, the positive drag effect can be as large as 25%.

In this Letter we address the fundamental issues regarding what one might expect when coupling quantum circuits in close proximity at the nanoscale. As the transport channel size is reduced towards the one-dimensional (1D) limit, charge flow across the channel becomes increasingly dominated by quantum processes. Owing to the long-range nature of the Coulomb potential, coupling two quantum circuits in close proximity (separated by a hard barrier of width $d$) may have profound effects on the current flow and on the equilibrium charge distribution in one wire when current is driven in another wire. First, when $d$ is only a few nanometres, tunnelling may occur between the two circuits and induce a current.

This tunnelling current is strongly suppressed with increasing $d$. Even after tunnelling becomes negligible, a non-zero potential develops across the channels, in contrast to our vertically coupled electrical design, in which coupling of electrical circuits results from the overlap of electron wave functions (typically 80 nm or greater) and the fringing fields of surface defined gates impose that the effective barriers between lateral 1D wires are soft and are no less than 80 nm. Thus, to construct coupled circuits in the 15 nm range, one must couple the circuits vertically. In this design, a hard barrier is introduced during the material growth process, allowing the coupling of electrical circuits over distances of only a few nanometres. The price to pay in this approach is the complex fabrication process required to define quantum wires with independent electrical contacts, as sketched in Fig. 1a–d.

Figure 3 shows the evolution of the conductance at a temperature of 0.33 K in each quantum wire as a function of gate voltage. Figure 3a was taken at a fixed upper plunger gate (UPL) of 0.33 K in each quantum wire as a function of gate voltage.

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Coupling two independent electrical circuits by proximity may lead to signals in one circuit, the origins of which are entirely from the neighbouring circuit, such as Coulomb drag. To measure this drag effect, a current $I_{\text{drive}}$ is set in one of the (drive) circuits. Under the condition of no current flow, a voltage $V_{\text{drag}}$ develops across the second (drag) circuit, defining a drag resistance $R_{\text{drag}} = -V_{\text{drag}}/I_{\text{drive}}$ that is a direct probe of electron–electron interactions. Coulomb drag is distinct from rectification and ratchets mechanisms where a voltage develops owing to a neighbouring current flow whose $I$–$V$ characteristics are highly nonlinear (with respect to $I_{\text{drive}}$) and non-symmetric with respect to probe inversion. In contrast, Coulomb drag is an equilibrium phenomenon that is linear, invertible with respect to probe symmetry, mutual, and present in ballistic and non-ballistic circuits.

The drag resistance measured in our quantum circuit is shown in Fig. 4a, together with the conductance of each wire. Coulomb drag peaks are observed concomitant with the opening of 1D sub-bands in either wire (see dotted lines in Fig. 4a). Momentum matching between both wires can explain the presence of the positive drag peaks when the wires have similar sub-band occupancies, but an enhancement of the electron–hole asymmetry as 1D channels open in the quantum wires appears more likely to explain the presence of positive peaks when the wires have different sub-band occupancies. In addition, negative Coulomb drag is observed in two clearly distinct regimes: one at low electronic density when the drag wire is close to or beyond depletion, and one at higher electronic density when $N_{\text{drag}} > 1$. Negative Coulomb drag has been previously observed at low density (for $N < 1$ in both wires) and attributed to 1D Wigner
crystallization. Although Wigner crystallization could explain the low-density negative drag signal in this Letter, it cannot explain the high-density negative drag. Negative Coulomb drag has been predicted to occur following a charge-fluctuation induced Coulomb drag model in asymmetric mesoscopic circuits, but more work is required to assess its consistency over the whole phase space of 1D Coulomb drag.

We show in Fig. 4b the temperature dependence between =0.4 K and ~6 K in both the high-density negative drag and the positive drag regimes. In either case, the drag effect survives without significant saturation down to the lowest temperature probed in this experiment, confirming the thermal equilibrium of the electrons in the quantum wires with the apparatus. The re-entrant negative drag signal disappears at $T \approx 1.2$ K, which is consistent with the system leaving the mesoscopic regime as the temperature length $L_T = \hbar v_F/|e|T$ is lowered from ~5.5 μm at 0.33 K to ~1.5 μm at 1.2 K, and becomes shorter than the system size. Figure 4c,d shows the linearity of the drag voltage with drive current (for small enough drive voltages, that is, empirically for $eV_{\text{drive}}/K_F \lesssim 3$ K) and the probe symmetry of the drag signal, confirming that the signals observed are consistent with Coulomb drag. For wires with a similar sub-band occupancy presented in Fig. 4a, the drag effect is ~2% of the drive voltage value. However, in wires with significantly different sub-band occupancy, this effect can be as large as 25%.

Coulomb drag between nanoelectronic circuits will become increasingly important as nanocircuitry becomes coupled by proximity. As nanostructure cross-sections become comparable to the three-dimensional screening length, the effective 1D screening length is expected to become large. Using typical doping values for silicon nanowires, the bulk Thomas–Fermi screening length $\lambda_T = \sqrt{\varepsilon E_F/6 \pi^2 n}$, where $\varepsilon$ is the electron charge, $n$ is the electron density, $\varepsilon$ is the silicon dielectric constant and $E_F$ is the Fermi energy, is estimated to be ~4 nm. Therefore, as nanowire diameter approaches this length scale, the previously screened Coulomb interactions will induce Coulomb drag signals in circuit elements located in close proximity. This drag effect is found to be as large as 25% of the drive voltage value, or up to 100 μV, for the structures presented in this Letter, which is far from negligible. Understanding the coupling between independently addressed...
conductive at the nanoscale, for example coupled nanowires for nanoprobing\(^1\).

**Methods**

**Device fabrication.** The wires were patterned on an n-doped GaAs/AlGaAs electron bilayer heterostructure with two 18-nm-wide quantum wells separated by a 15-nm-wide Al\(_{10.25}\)Ga\(_{0.75}\)As barrier. After a mesa-structure was wet-etched using phosphoric acid into the double quantum well heterostructure, Ge–Au–Ni–Au ohmic contacts were deposited on the structure (Fig. 1a). Following an annealing at 420 °C for 60 s, a set of two Ti–Au split gates, consisting of a T-shaped pinch-off gate and a plunger gate, was defined on the surface of the heterostructure. The off-mesa patterning was done using photolithography and electron-beam lithography to pattern the gates on-mesa (Fig. 1b). The thickness of the gates was 160 nm off-mesa and 60 nm on-mesa. A set of four alignment marks was also patterned simultaneously to the patterning of the electron-beam lithography-defined top gates. These marks were used to align the lower gates to the upper ones. The upper side processing was complete, bare GaAs was glued on top of the substrate and the sample flipped, mechanically lapped and chemically etched until the lower 2DEG side processing was complete, bare GaAs was glued on top of the substrate and the sample flipped, mechanically lapped and chemically etched until the lower 2DEG sample flipped, mechanically lapped and chemically etched until the lower 2DEG was only ≈150 nm away from the lower surface (now on top of the device, as shown in Fig. 1c), following an EBAS techniques. Two stop-etch layers were incorporated in the original heterostructure: a larger AlGaAs stop-etch layer and a thinner GaAs stop-etch layer. The purpose of the AlGaAs stop-etch layer was to flatten out the unevenness arising from the lapping process during the subsequent citric wet-etching. Indeed, the citric acid etch rate is greatly reduced in AlGaAs compared to GaAs, allowing the surface of the device to be smoothed after mechanical lapping. After the citric etch, the remainder of the AlGaAs stop-etch layer was etched using hydrofluoric acid, leaving only the thin GaAs stop-etch layer, which was grown to neutralize the etching. To ensure that no off-mesa leakage occurred between the upper and lower gates, a thin 60 nm layer of Al\(_{0.3}\)Ga\(_{0.7}\)As was deposited on the top of the device using atomic layer deposition. Using phosphoric acid, vias were then etched through the surface to enable electrical connection to the ohmic contacts and to the upper split gates on the buried surface of the device. Finally, using a combination of photolithography and electron-beam lithography, another set of two Ti–Au split gates was defined on the lower side of the sample and aligned with the upper gates using the previously deposited alignment marks buried underneath the surface. It is possible to observe these marks using a scanning electron microscope or an electron-beam lithography tool with an accelerated voltage greater than or equal to 30 kV, and therefore precisely align the lower and upper gates. The end result is presented in Fig. 1d.

**Device operation.** The pinch-off gates were first adjusted so that they principally deplete the 2DEG closest to them. While each pinch-off gate can deplete both 2DEGs for sufficiently large applied negative voltage, a 0.3 V (0.15 V) wide plateau (where the conductance across the device is roughly constant) is observed when sweeping the upper (lower) pinch-off gate. On this plateau, the 2DEG closest to the gate is fully depleted whereas the other one is only partially depleted. For the device presented in this Letter, the lower gates create a larger partial depletion than the upper gates, causing the contact resistance to the upper wire to be larger than the contact resistance of the lower wire. The positioning within the plateau is adjusted such that the tunnelling resistance between both layers is larger than 25 MΩ. In such experimental configuration, there is minimal tunnelling between the upper and lower layer contacts. Indeed, the depletion mechanism of the pinch-off gates results in a coupling of each side of the device to a single layer, allowing simultaneous and independent measurement of both layers, unlike in the device presented by Bielejec et al.\(^{15}\) Subsequently, adjusting both the LPL and UPL voltages allows for independent tuning of the sub-band occupancy in each independent wire.

**Device characterization.** Measurements performed on the sample post-processing with the split gates grounded yielded an electronic density of 1.1 (1.4) × 10\(^{11}\) cm\(^{-2}\) for the upper (lower) 2DEG, and a combined mobility of 4.0 × 10\(^{5}\) cm\(^2\) V\(^{-1}\) s\(^{-1}\). Transport measurements on individual quantum wires were performed in a He refrigerator at a temperature of 330 mK using a constant 50 μV excitation at 9 Hz in the lower wire and 13 Hz in the upper wire in a two-contact configuration. The Coulomb drag measurements were performed in a constant-current mode where 4.5 nA at 9 Hz was sent through the drive wire. In this configuration, the out-of-phase current was always much smaller than the in-phase current.

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**Figure 4 | Drag resistance of the coupled quantum circuits.** a, Drag resistance (red curve, left axis) is shown as a function of LPL voltage together with the conductance in the drive wire (grey curve, right axis) and in the drag wire (blue curve, right axis) for fixed UPL = −0.23 V. The presence of peaks in the drag resistance concomitant with the opening of 1D channels in either wire is highlighted by dotted lines. b, Temperature dependence of the Coulomb drag signal at the peak of the positive drag regime (black curve) for UPL = −0.25 V and LPL = −1.53 V, and in the high-density negative drag regime (blue curve) for UPL = −0.15 V and LPL = −2.96 V. c, Drag voltage as a function of drive current for the low-density negative drag regime, the positive drag regime and the high-density re-entrant negative drag regime. In all three regimes, the drag voltage is linear with drive current for \(v_{\text{drive}}/k_B T \lesssim 3\) K. The current used for the drag measurement (4.5 nA) was always within the linear drag regime. d, Drag voltage as a function of LPL for both positive (black curve) and negative (red curve) drive currents showing that the signal is independent of the drive current direction.
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M.P.L. designed and conceived the experiment; J.L.R. performed the growth of the double quantum well heterostructures. D.L. fabricated and characterized the samples, and performed the Coulomb drag measurements. G.G., M.P.L. and D.L. co-wrote the Letter and all authors discussed the results and commented on the manuscript.

Additional information

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