Coulomb drag between parallel quantum wires

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Recently one-dimensional electron systems have attracted a great deal of interest both experimentally and theoretically. In such systems, strong electron correlation leads to non-Fermi-liquid characteristics. Coulomb drag measurements on parallel coupled quantum wires can be used to probe the interaction effects in quantum wires more directly than those of straightforward electron transport. This is because in conventional electron transport, conductance of the wires is determined largely by the coupling to the Fermi reservoirs whereas the Coulomb drag occurs directly and solely within the strongly interacting regions of the wires. Here we report our experimental observation, using coupled quantum wires defined by schottky gates fabricated on a n-AlGaAs/GaAs 2DEG based heterostructure (Fig.1), of Coulomb drag between the wires which are related to the interaction effect in the wires.

Coulomb drag is the momentum transter between electrons in isolated layers due to the direct Coulomb interaction. Electrons moving in one of the layers (drive layer) generate a fluctuation of electric field in the other layer (drag layer), resulting in a voltage drop in the drag layer if no current flows through it. The drag resistance R_{D} is experimentally determined as $-\frac{V_{\mathrm{drag}}}{I_{\mathrm{drive}}}$, where I_{drive} is the current injected into the drive layer and $-V_{\mathrm{drag}}$ is the voltage drop induced in the drag layer(See Fig.1). It is difficult to observe this phenomenon in 2 or 3 dimensional electron systems because the screening effect is strong: The Coulomb drag is generally smaller than the phonon mediated drag[1]. However, in 1 dimensional electron systems, Coulomb drag is much stronger than the phonon drag and we can observe it. Especially for long wires, Tomonaga-Luttinger liquid effect (TLL effect) enhances the Coulomb drag significantly: Drag resistance of the order of kΩ is observed[2].

Fig.1 shows our experimental set up for the drag measurements. We measure the drag resistance as a function of side gate voltages, Vg_{drive} and Vg_{drag}. In coupled quantum wires, R_{D} is positive for usual Coulomb drag as long as momentum is conserved. This positive drag becomes maximal when the Fermi verocity is aligned between the two wires. For Fermi liquid wires, such as coupled short wires or high electron density wires, this peak as a function of Vg should be sharp and the height of it deacreases as the temperature decreases due to the reduction of the phase space. However, our results for long wires ($> 1\mu$m) show that this peak is much broader than $k_{\mathrm{B}}T$ and its height increases as the temperature decreases. This behavior is explained as the electron density locking between the coupled TL liquids, i.e., the model of strongly coupled quantum wires[3].

We also observe that R_{D} becomes negative when the drive wire has very low electron density[2]. The"negative" resistance means that the electrons in the drive wire drag holes in the drag wire. By applying a magnetic field, we can more clearly observe this phenomenon because negative drag is enhanced and observed in a wider range of electron density in the drive wire, i.e., drag is negative even when electron density in the drive wire is not so close to pinch-off. This relates to the

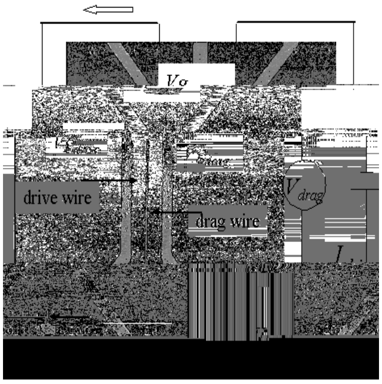

Figure 1: SEM image and measurement set up (Wire length = 2 μm). The tunneling current between the wires is completely suppressed by the center gate. We can also control electron density in the wires by biasing the two side gates, Vg_{drive}, Vg_{drag}.

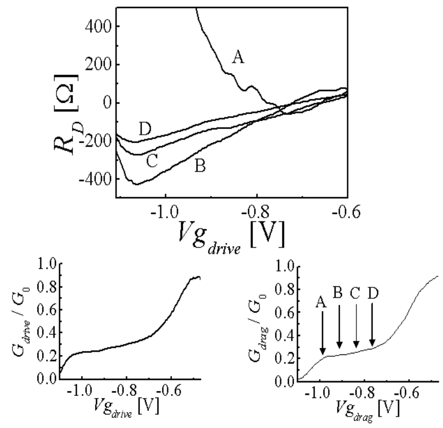

Figure 2: Drag resistance observed for the 4 μm long coupled wire in a magnetic field of 4.5 T and conductance of the two wires in the unit of $G_0 = \frac{e^2}{h}$. Line (A) is for $Vg_{\mathsf{drag}} = -0.98$ V, (B) for $Vg_{\mathsf{drag}} = -0.92$ V, (C) for $Vg_{\mathsf{drag}} = -0.86$ V, and (D) for $Vg_{\mathsf{drag}} = -0.80$ V.

shrinking of the wave function and the quenching of the kinetic energy and the resulting increase of the effective Coulomb interaction. Hence the negative drag regime is considered to coincide with the regime where electrons in the drive wire behave as particles: the sliding Wigner-crystal like state, as long as interaction works between the particles. We assign the origin of the observed negative drag to the correlation effect, such that correlation holes are induced in the drag wire. We conclude from our experimental results that the formation of image charges, induced by a sliding Wigner-crystal-like state in the drive wire, is the most plausible candidate for the correlation holes. However, for fixed value of the electron density in the drive wire, the drag becomes negative only in a limited range of electron density in the drag wire. Our experimental results show that the negative drag maximizes when the electron density in the drag wire is near the left edge of the first plateau ($\nu = 1$ for high magnetic field, $\nu = 2$ for low magnetic field). Away from the maximum, where the drag wire electron density is very low, the electron correlation in the drag wire is screened by the surface gate. By contrast, for sufficiently high drag wire density, screening in the wire is effective. These results indicate that negative drag cannot occur without some correlation effect in the drag wire. Note also that we should account for the momentum conservation problem. Our wires have many scattering centers represented by impurities which can absorb the necessary momentum.

In the negative drag, each particle injected into the drive wire causes an electric potential pulse to propagate in the drag wire. Because the compressibility of the interacting 1D electrons in the drag wire is much lower than the 2DEG region in the leads, a pulse entering from one lead results in the ejection of electrons out of that same, nearby lead: a kind of electron splash. Impurities are required to conserve momentum in this process. As the pulse progresses under the driving electric field, the image charge or hole formed by the expulsion of electrons in the drag wire will accompany the negative charge in the drive wire. Finally, when the pulse exits to the drain, the corresponding exit of the hole in the drag wire will be manifested as an inflow of electrons from the drain.

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