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Towards Coulomb Drag in Vertically Coupled Quantum Wires with Independent Contacts

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Abstract

We report the details of design and fabrication of independently-contacted, vertically-coupled quantum wires using the Epoxy-Bond-And-Stop-Etch (EBASE) technique. These nanostructures are fabricated in high quality GaAs/AlGaAs parallel double quantum well heterostructures and are intended for Coulomb drag measurements of quantum wires. They will allow us to explore Coulomb drag in one-dimensional structures in a regime of small interlayer separation where the drag signal is expected to be stronger and less affected by phonon drag.

Key words: Quantum wires, nanostructures, Coulomb drag, Vertical geometry
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1. Introduction

One dimensional structures have shown a number of striking transport properties. Apart from the universal quantization steps in units of $2e^2/h$ [1,2], most of these properties are coming from the enhancement of electron-electron interactions induced by the strong confinement of electrons in one dimension. This enhancement renders the Fermi-Liquid (FL) theory typically used in higher dimensions inadequate to describe electrons' behavior. This model has to be replaced with the Luttinger-Liquid (LL)theory, describing best the electrons behavior in one-dimension. This theory leads to many interesting predictions, including spin-charge separation. [3,4]

A lot of expectations are put into coupled nanostructures to understand these non-FL characteristics of 1D systems. Coulomb drag is a measurement achievable within coupled quantum wires that might give insight into LL theory. Coulomb drag consists in driving a current I_{drive} into one of the wire, the drive wire. At the same time, current must be prevented to flow in the other wire, the drag wire. It this case, e^--e^- scattering causes the electrons in the drag wire to pile up on one side, creating a voltage difference V_{drag} across this wire. The quantity usually presented is the transresistance, or the drag resistance, which is defined as the drag voltage divided by the drive current : $R_D = V_{drag}/I_{drive}$.

In this paper, we report on the design and the fabrication of vertically-coupled, independently-contacted

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quantum wires and we present some preliminary results on the tunnel rate as a function of the interlayer barrier in AlGaAs-GaAs MBE growth heterostructures.

2. Theoretical and experimental background

Coulomb drag in caused by e^--e^- scattering via Coulomb interactions conserving both energy and momentum. At low 1D electron density, Coulomb drag is expected to be stronger due to the enhancement of Coulomb interactions and the reduction of screening coming from the 1D confinement.[5] The drag can occur either when electrons are scattered along the drive current direction (positive drag) or opposite to it (negative drag). The latter is expected at really low electron density while the former is expected in the other case.[6] Coulomb drag has been thoughtfully studied in bilayer systems where the drag was consistent with FL theory and showed a quadratic dependence with temperature.[7–10]

In 1D within LL theory, the temperature dependence of the Coulomb drag is theorized to exhibit a richer dependence than in FL theory. The main contribution to the transresistance comes from inter-wire backscattering. There are four main temperature regions over which the temperature dependence of the drag behavior changes drastically. These regions are defined by the temperature at which the thermal wavelength of the electrons, T_L, becomes of the order of the system size and by the energy (or mass) M of a soliton. Solitons are single localized waves that are very robust and can interact strongly. They form spontaneously in systems described by non-linear differential equations. In the low temperature regime, where $T < T_L$, there is strong coupling and the drag decreases linearly with temperature due to soliton tunnelling. If the temperature is even lower such that $T < \sqrt{(T_L M)} exp(-M/T_L)$, the Coulomb drag then decreases as T^2. If the thermal wavelength is bigger than the system size, but $T < M$, thermally activated solitons cause an activated behavior of the drag resistivity such that

$$\rho_D(T) \approx \tilde{\rho_0} e^{M/T}, \tag{1}$$

where ρ_0 is a constant. In the high temperature regime, where $T > T_L; M$, the Coulomb drag resistivity depends on the strength of the e^--e^- interactions in a power-law fashion.

$$\rho_D(T) \approx \tilde{\rho_0} \left(\frac{T}{E_0}\right)^{4K-3}, \tag{2}$$

where E_0 is a constant of the order of the Fermi energy and K is a parameter accounting for the strength of the charge interactions. If there are no interactions, K is unity and one obtains a linear increase of the drag with temperature, as predicted by FL theory. Thus, exploring the different regimes of the Coulomb drag can give significant insight on the e^--e^- interaction strength in 1D.

Coulomb drag measurements between quantum wires have already been measured in several experiments. However, these measurements have been made either in an horizontal geometry [6,11]. In these geometries, the two wires are separated by a soft electrostatic barrier. Due to this soft barrier, the wires need to be farther apart to minimize the interwire tunnelling. This separation leads to a weaker Coulomb drag signal it decreases exponentially with interwire separation. However, phonon drag doesn't exhibit the same decay and is still strong at interwire distance higher than 100 nm. [12] Therefore, soft barriers cause the drag signal to be significatively influenced by the phonon drag. Creating vertically-coupled wires would allow us to explore the short interwire separation regime of the Coulomb drag and to minimize phonon-induced drag since such wires have a hard MBE defined barrier, which allows smaller tunnel conductance for a given interwire distance.

3. Device fabrication

The vertically-coupled quantum wires reported here are fabricated in GaAs-AlGaAs double quantum well heterostructure using electrostatic TiAu split gates to define the wires. A sketch of the device and the effect of applying a negative bias on the gates is shown on figure 1(a). The device consists of 2 pinch off gates and 2 plunger gates, one on each side of the device, forming wires that are 2 μm long and 0.5 μm wide. These dimensions were chosen as a balance between the need to observe ballistic quantization steps, usually sharper in short wires, and the need to observe a strong enough drag signal, which will be larger in longer wires. In order to deposit the metallic gates on both side of the double quantum well, we employ the epoxy-bond-and-stop-etch (EBASE) technique [13]. This technique allows the bottom and the top split gates to be approximately 200 nm from their respective quantum well, sufficient proximity to form well confined wires. A scanning electron microscope picture of the device made on a GaAs-AlGaAs sample with a 12 nm barrier is shown on figure 1 (b). The gates are patterned such that, when an appropriate negative bias is applied on the gates, only regions C & D and G & H are electrically connected. This connection occurs through a quantum wire; thus one can probe independently both wires. An arbitrary number of conduction sub-bands can be occupied depending on the bias applied on the gates.

In order to determine which barrier height we should use in our double quantum well structure, we measured the tunnelling rate as a function of the height of the barrier. The results are shown in figure 2. The data show the expected exponential decay behavior for tunnelling and follow the relation

$$C = 0.88e^{-1.63d}, \quad (3)$$

where C is the tunnelling conductance and d is the barrier height. The wires described previously have a total surface of 1 μm^2. Assuming that the rate of 2D and 1D tunnelling are similar, we get that a 15 nm height barrier would only contribute to 10^{-9} siemens to the interwire conduction, three orders of magnitude smaller than the drag conductance measured by Debray's group. [11]

Tunnelling measurements have already been made for vertically coupled quantum wires with small interlayer barrier and [14] for cleaved edge overgrowth wires [15]. The design used in the former case used separate gates to achieve independent contacts. These gates were close to the wires and were thus affecting their density profile, making it rather nonuniform. This is the reason why we used a different design to create our vertically-coupled quantum wires.

In the future, we will make measurements on these vertically-coupled quantum wires. An important step will be to map completely the occupied sub-bands of each quantum wire as a function of the different gate voltages. This aspect won't be trivial since all the gates are capacitively coupled to each other. We will then be ready to measure Coulomb drag.

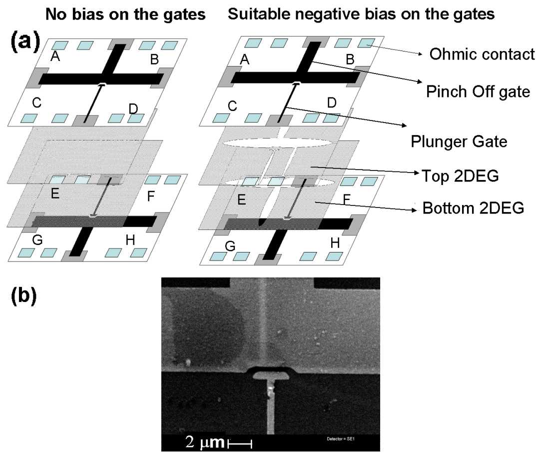

Fig. 1. **(a)** Sketch of the design used for the double quantum wires fabrication. We can see how applying a suitable negative bias on the gates depletes the 2DEGs. **(b)** A SEM picture of the double quantum wires. One should note that the gate on the other side of the wafer (top side) appears as a faint white arm.

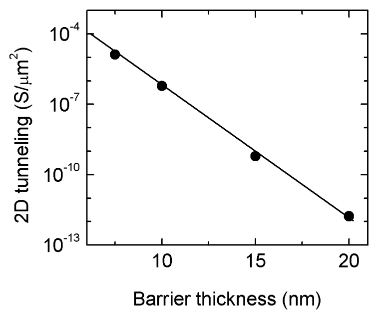

Fig. 2. Log plot of the tunnelling conductance as a function of the interlayer distance of double quantum well heterostructures. The data follows an exponential decay with the barrier height best described by $C = 0.88e^{-1.63d}$.

4. Conclusion

In conclusion, we have fabricated vertically-coupled quantum wires with independent contacts, using split-gate and EBASE techniques. The vertical geometry and the rigid barrier between the two layers will allow us to make Coulomb drag measurements in a regime that has never been explored before. This could provide useful information on the many-body interactions that electrons experience through Coulomb scattering.

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