Non-Coulombic frictional drag currents in coupled
LaAlO$_3$/SrTiO$_3$ nanowires

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Abstract

Frictional drag phenomena are investigated in coupled nanowires formed at LaAlO$_3$/SrTiO$_3$ heterointerfaces. The weak decay of drag resistance with increasing wire separation rules out Coulomb interactions as the coupling mechanism. The observed unidirectional current drag is explained using a simple model that invokes slight asymmetries within the nanowires. These results provide new insights into non-Coulombic electron-electron interaction effects that must be accounted for in any full description of electron transport at oxide interfaces.
When two conductors are in close proximity, a current driven through one (the “drive” system) may induce a voltage in the other (the “drag” system). This effect is most generally known as frictional drag or Coulomb drag and was first proposed by Pogrebinskii [1] as a method to probe correlations among the charge carriers of the system. Drag measurements have since been carried out in coupled 2D-3D semiconductor systems [2, 3], 2D-2D semiconductor [3–7] and graphene [8, 9] systems, 1D-1D nanowires defined from semiconductor 2DEGS [10–12], and in coupled semiconductor quantum dots [14]. These drag signals have been dominated by Coulomb interactions; at large separations, non-Coulombic interactions become apparent [15–17].

The heterointerface between the complex oxides LaAlO$_3$ and SrTiO$_3$ (LAO/STO) [18] possesses a rich phase diagram that is mainly derived from the properties of SrTiO$_3$ itself. The interface exhibits a reversible, metal-insulator transition [19], which can be controlled locally using conductive atomic force microscopy (c-AFM) lithography [20, 21]. The interface also shows a variety of electronically-tunable properties such as spin-orbit coupling [22, 23], ferromagnetism [24], and attractive electron-electron interactions [25] which lead to superconductivity [26, 27] and electron pairing without superconductivity [28]. Many of these properties are sensitive to the electron-electron interactions, making frictional drag of significant interest as a direct probe of these interactions.

Here we report frictional drag measurements in coupled LAO/STO nanowires. Devices are fabricated by c-AFM lithography on LAO/STO heterointerfaces with 3.4 unit cells (u.c.) of LAO deposited on an STO substrate by pulsed-laser deposition (PLD). Details of the growth conditions are described elsewhere, e.g., Ref. [13]. The frictional drag system (Fig. 1(a)) consists of two parallel nanowires of width $w \sim 10$ nm, length $L = 400$ nm to 1.5 $\mu$m, and separation $d = 40$ nm to 1.5 $\mu$m. One nanowire has four terminals (wire 2), allowing for 4 terminal measurements; different from the ideal configuration in Fig. 1(a), the other wire only has three terminals (wire 1) due to limitations of the instrument.

Experiments are generally performed by sourcing current $I_{\text{drive}}$ in the drive wire and measuring an induced voltage $V_{\text{drag}}$ or current $I_{\text{drag}}$ in the drag wire. A DC current $I_1 = I_{\text{drive}}$ is sourced in wire 1 by applying a voltage $V_{s1}$. The resulting voltage measured in wire 1 is $V_1$ and the induced voltage measured in wire 2 is $V_2$. The 3-terminal resistance of wire 1 is calculated as $R_{11} = dV_1/dI_1$, while the drag resistance of wire 2 is given by $R_{\text{drag}} = R_{21} = dV_2/dI_1$. The role of the source and drag wires can also be swapped: when
FIG. 1. Experimental setup and typical frictional drag measurements at large $B$. (a) A schematic of the coupled nanowires (green lines) on LAO/STO of length $L$, width $w$, and interwire separation $d$. The device shown above is setup to measure the induced $V_{\text{drag}} = V_2$ across wire 2 by $I_1$ sourced by the voltage $V_{s1}$ through wire 1. (b,c) $R_{\text{drag}}$ for device 2B for (b) wire 2 ($R_{21}$) (c) wire 1 ($R_{12}$). (d) $R_{12}$ for device 1A. Bottom panel of (b, d) show linecuts of corresponding $R_{\text{drag}}$ at different $B$.

Current is sourced in wire 2, the 4-terminal resistance of wire 2 is given by $R_{22} = dV_2/dI_2$ and the drag resistance of wire 1 is $R_{\text{drag}} = R_{12} = dV_1/dI_2$. All reported measurements are carried out in a regime in which $R_{\text{drag}}$ is mostly independent of temperature, $T \leq 100$ mK. To minimize leakage current between wire 1 and wire 2, drag measurements are performed well below the measured interwire breakdown voltage.

In Figs. (b,c), $R_{\text{drag}}$ is plotted as a function of $I_{\text{drive}}$ and $B$ for Device 2B (see Table I for device parameters). $R_{\text{drag}}$ is largely antisymmetric in $I_{\text{drive}}$ regardless of which wire serves as source, as is illustrated by the linecuts at constant magnetic field. Pronounced oscillations in $R_{\text{drag}}$ are also observed as a function of magnetic field, with the pattern being different depending on which wire is the source. For wire 2 (Fig. (b)), $|R_{\text{drag}}|$ is largest near $|I_{\text{drive}}| \sim 50$ nA and $B \sim 7$ T, with a secondary local maximum occurring near $B \sim 4$
TABLE I. The $L$, $d$, 2-, 4/3-terminal, and drag resistances of wire 1 and wire 2 for several devices. The device shown in Figs. 1(b,c), 2, and 3 is marked in boldface.

| Device | $L$  | $d$  | $R_{2T,1}$ | $R_{2T,2}$ | $R_{11}$ | $R_{22}$ | $R_{\text{Drag},1}$ | $R_{\text{Drag},2}$ |
|--------|------|------|------------|------------|----------|---------|---------------------|---------------------|
| 1A     | 400 nm | 40 nm | 58-72 kΩ  | 42-48 kΩ  | 32-43.5 kΩ | 8.4-9.2 kΩ | 20 Ω                | 60 Ω                |
| 1B     | 400 nm | 40 nm | 22-30.8 kΩ | 25.5-33.5 kΩ | 8.6-12.5 kΩ | 14-18.3 kΩ | 14.1 Ω              | 4 Ω                 |
| 1D     | 1 μm  | 300 nm | 36.5-46.5 kΩ | 25-45.8 kΩ | NA        | 8.7-18 kΩ | 50.6 Ω              | 23.2 Ω              |
| 1E     | 1 μm  | 450 nm | 40-108 kΩ | 29-34 kΩ | NA        | 6.4-7.5 kΩ | 200 Ω              | 38.5 Ω              |
| 1F     | 1.5 μm | 550 nm | 27-35 kΩ | 29-63.4 kΩ | NA        | 7.8-11.8 kΩ | 15 Ω                | 52 Ω                |
| 2A     | 1.5 μm | 550 nm | 33-76.6 kΩ | 22-29 kΩ | NA        | NA      | 27 Ω                | 26 Ω                |
| 2B     | 1.5 μm | 550 nm | 23-36.2 kΩ | 22-51 kΩ | 11-16 kΩ | 3.7-5.5 kΩ | 19 Ω                | 41 Ω                |
| 2C     | 1.5 μm | 1.5 μm | 16.5-26.5 kΩ | 22-37 kΩ | 10.2-14.8 kΩ | 2.7-4.1 kΩ | 10 Ω                | 8.5 Ω                |
| 3A     | 400 nm | 200 nm | 50-127 kΩ | 26.6-37 kΩ | 29-98 kΩ | 5.2-6.7 kΩ | 136 Ω               | 86 Ω                |

In wire 1, oscillations still appear, but are less pronounced (Fig. 1(c)). In some devices, the oscillations of $R_{\text{drag}}$ in magnetic field are more extreme and can even change the parity of $R_{\text{drag}}$, as shown for Device 1A in Fig. 1(d).

By comparing the maximum $R_{\text{drag}}$ for devices with various $L$ and $d$ (see Table I), we see that the drag resistance does not decrease significantly for a large range of separations $d$. If $R_{\text{drag}}$ arose primarily due to Coulomb interactions between the charge carriers, we would expect, due to the rapidly decreasing interaction between the nanowires [29, 30], that the signal would decay quickly as the separation is increased. We therefore conclude that the dominant interactions between the nanowires are non-Coulombic in nature.

Changes in the sign of $R_{\text{drag}}$ as $B$ varies were previously observed in semiconductor nanowires [11]. In that case, the system was tuned to a very low electron density and the oscillations were attributed to the onset of Wigner crystallization in the nanowires due to the large magnetic field. The coupling between the charge densities of each wire then allowed electrons in the drive wire to drag holes from the leads through the Wigner crystal in the drag wire, changing the sign of $R_{\text{drag}}$. For LAO/STO nanowires, this mechanism appears not to apply due to the non-Coulombic character of the interactions, as discussed above.

To better understand the origin of the oscillations of $R_{\text{drag}}$ in $B$, we consider how the
FIG. 2. Four-terminal resistance, zero-bias $dR_{22}/dI_2$ and $R_{\text{drag}} = R_{21}$ of wire 2. (a) Top panel, four-terminal resistance $R_{22}$ of wire 2 as a function of $B$ and $I_2$. Bottom panel, line profiles of $R_{22}$ at -9, -7 and -3 T. Line profiles at higher $B$ are shifted 1kΩ compared to lower $B$. (b) Top panel, $dR_{22}/dI_2$ of wire 2 at $I_2 = 0$ nA as the magnetic field is varied. Bottom panel, line cuts of $R_{21}$ from Fig. 1(b) at $I_1 = -50$ nA (green) and $I_1 = 50$ nA (red).

electronic structure of the nanowire changes with $B$. The four-terminal resistance $R_{ii}(B)$ yields information that is strongly correlated with the observed asymmetry. Fig. 2(a) shows $R_{22}$ to be highly asymmetric with the asymmetry at $I_2 = 0$ changing as a function of $B$, which is highlighted by the line cuts in the bottom panel. $dR_{22}/dI_2$ at zero bias provides a useful quantitative measure of the observed asymmetry (Fig. 2(b)), which is highly correlated with the drag resistance $R_{\text{drag}} = R_{21}$. The strong antisymmetry of $R_{\text{drag}}$ is highlighted by taking line cuts of $R_{\text{drag}}$ at $I_{\text{drive}} = 0, \pm 50$ nA, as shown in the bottom panels of Fig. 2(b).

The antisymmetric nature of $R_{\text{drag}}$ with respect to $I_{\text{drive}}$ means that the drag current $I_{\text{drag}}$ is unidirectional. A schematic of a current drag measurement is shown in Fig. 3(a): a current $I_1$ is driven through wire 1 by a voltage $V_{s1}$, resulting in an induced drag current $I_2 = I_{\text{drag}}$ in wire 2. $I_2$ flows through the entire measurement circuit, leading to an increase in the noise when compared to voltage measurements. From these measurements, $I_{\text{drag}}$ is indeed found to be symmetric in $I_{\text{drive}}$, as shown in Fig. 3(b). The symmetry is further emphasized by the line cuts at constant magnetic field in the bottom panel and by the overlap of line cuts at $I_{\text{drive}} = \pm 70$ nA. Direct measurement of the drag current $I_{\text{drag}}$ in wire
FIG. 3. Current drag measurement setup and magnetic field dependence of drag current. (a) The configuration for current drag measurement. By making wire 2 a closed loop, drag current $I_{\text{drag}} = I_2$ can be measured. (b) Top panel, $I_{\text{drag}}$ measured through wire 2 from Fig. 1(b). Line cuts at fixed $B$ are shown in the bottom panel, illustrating the unidirectional nature of $I_{\text{drag}}$. Line cuts at higher $B$ are shifted 40pA upwards compared to lower $B$. Line cuts of drag current $I_2$ at $I_1 = -70\text{nA}$ (red) and 70nA (blue) are shown in the right panel. $I_2$ is symmetric over the whole measurement $B$ range.

2 for Device 2B (Fig. 3) confirms the unidirectional nature of the current. Note that the actual direction of the drag current is itself magnetic-field dependent.

The observation of unidirectional currents has not been previously reported in nanowire geometries, to our knowledge. The generation of such unidirectional currents has been
FIG. 4. Model system and calculated currents. (a) The theoretical model consists of two "nanowires" connected to leads, labeled 1 through 4. Electron-electron interactions are encoded through the parameters $U_{\text{Wire}}$ between sites of each wire and $U_{\text{Sym}}$ and $U_{\text{Asym}}$ between sites in different wires. (b) The drag current calculated through the system for $U_{\text{Wire}} = 20t$, $U_{\text{Sym}} = 0.1t$, and $T = 2t$ when $U_{\text{Asym}} = 0.01t$ and $\epsilon_{12} = \epsilon_{11} = 0$ (red) and when $U_{\text{Asym}} = 0$ and $\epsilon_{12} = 0.01t$, $\epsilon_{11} = 0$ (blue).

explored in coupled quantum point contacts [32] and quantum dots [14, 33–35]. In both cases, momentum is not conserved in the point-like interaction region and the drag currents are produced by energy transfer alone. Thus, unidirectional drag currents may be produced by engineering the leads of the system. For nanowires, the extended nature of the system leads to strong momentum conservation if translational symmetry is not broken and asymmetry within the leads is insufficient to cause unidirectional drag currents. Instead, there must be an asymmetry within the coupled nanowires to break the translational symmetry and weaken momentum conservation.

To show that symmetry breaking leads to unidirectional current, we consider a minimal model where the symmetry of the system may be broken within the nanowires. Each
nanowire is modeled as a series of sites, two for each nanowire and four sites total (Fig. 4(a)). The resulting Hamiltonian for the system is

\[
H_S = \sum_{\alpha} \left[ -t \left( c_{\alpha,1}^\dagger c_{\alpha,2} + \text{h.c.} \right) + U_{\text{Wire}} n_{\alpha,1} n_{\alpha,2} \right] + \sum_{\alpha,i} \varepsilon_{\alpha,i} n_{\alpha,i} + \frac{1}{2} \sum_{i,j} U_{ij} n_{1,i} n_{2,j},
\]

where \( n_{\alpha,i} = c_{\alpha,i}^\dagger c_{\alpha,i} \) is the number operator for site \( i \) in wire \( \alpha \), \( t \) is the hopping amplitude between sites of the same wire, \( U_{\text{Wire}} \) is the interaction between two electrons in the same wire, and \( \varepsilon_{\alpha,i} = \epsilon_{\alpha,i} - \mu_{\alpha,i} \), with \( \mu_{\alpha,i} \) the chemical potential and \( \epsilon_{\alpha,i} \) the single-particle energy of site \( i \) in wire \( \alpha \). The two wires are coupled by the interaction term \( U_{ij} \) between sites \( i \) and \( j \) in different wires.

In order to calculate the current through the system, we include coupling to the environment by introducing four leads (Fig. 4(a)) labeled 1-4. These leads are described by the Hamiltonian

\[
H_L = \sum_{\sigma,k} E_{\sigma,k} n_{\sigma,k}
\]

and couple to the system through the term

\[
H_{LS} = -t \sum_{k} \left( b_{1,k}^\dagger a_{1,1} + b_{2,k}^\dagger a_{1,2} + b_{3,k}^\dagger a_{2,1} + b_{4,k}^\dagger a_{2,2} + \text{h.c.} \right),
\]

where \( n_{\sigma,k} = b_{\sigma,k}^\dagger b_{\sigma,k} \) is the number operator for state \( k \) in lead \( \sigma \) and \( E_{\sigma,k} \) is the energy of the state \( k \) in the lead \( \sigma \).

Assuming that the leads are thermalized and Markovian, we derive a master equation for the time evolution of the density matrix of the system \( \rho_S \). Using the solution for \( \rho_S \) in the steady state, we find that when the symmetry is broken by either \( \epsilon_{1,1} \neq \epsilon_{1,2} \) or \( U_{ij} = \delta_{ij} (U_{\text{Sym}} + \delta_{2} U_{\text{Asym}}) \) the resulting \( I_{\text{drag}} \) becomes unidirectional, as shown in Fig. 4(b). Furthermore, the magnitude of \( I_{\text{drag}} \) can vary as a function of \( U_{\text{Asym}} \) and \( \epsilon_{1,1} - \epsilon_{1,2} \).

Asymmetry introduced within the devices leads to the unidirectionality of \( I_{\text{drag}} \) as well as the oscillatory behavior in \( B \). The unidirectionality of \( I_{\text{drag}} \) is the result of a broken translational invariance from the asymmetry between the left/right sides of the system. As a result of magnetic depopulation acting on the system, the degree of the asymmetry, characterized in the minimal model by \( U_{\text{Asym}} \) and \( \epsilon_{1,1} - \epsilon_{1,2} \), can change as a function of \( B \), with different portions of the wire being depopulated at different rates. This is supported
by other theoretical work showing that magnetic depopulation can lead to large changes in 
$R_{\text{drag}}$ as the bottom of a band is crossed [30].

While the origin of this non-Coulombic interaction is not at all understood, the long-range 
nature may prove useful in energy harvesting applications [36, 37] in which noise in the drive 
wire is rectified in the drag wire [38]. The long-range nature of the interaction allows the 
noise source to be placed far from the energy harvesting wire. Apart from applications, this 
strong interaction is worth understanding as it may be related to the strong electron-electron 
attraction that leads to pairing and superconductivity in STO-based heterointerfaces [25-28].

We are grateful to David Pekker for helpful discussions. Work at the University of 
Pittsburgh was supported by funding from the DOE Office of Basic Energy Sciences under 
award number DOE de-sc0014417. Work at the University of Wisconsin was supported 
by funding from the DOE Office of Basic Energy Sciences under award number DE-FG02-
06ER46327. Theoretical portion of this work (A.T-T.) supported in part by ONR N00014-
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