Hysteretic Hall resistance at the LaAlO$_3$-SrTiO$_3$ interface - interplay between superconducting and ferromagnetic properties

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Abstract. The conducting interface formed between the two insulators LaAlO$_3$ (LAO) and SrTiO$_3$ (STO) has been shown to have both magnetic and superconducting properties. As was reported in an earlier publication, the superconducting and the magnetic phases coexist simultaneously in this system [1], with superconductivity being tuned by an applied gate voltage. Here we report on the transverse (Hall) magnetoresistance of the interface as a function of the gate voltage, which tunes the density of carriers at the interface. Not only is the Hall resistance hysteretic, due to the magnetic order in the system, but also highly non-linear in the low field region. The interaction between the superconducting vortices and the combined external and intrinsic (hysteretic) fields gives rise to the complex structure in the Hall data.

The two dimensional conducting gas formed at the interface between LAO and STO has attracted a lot of attention since its discovery in 2004 [2]. The system exhibits a rich variety of behaviour including superconductivity [3, 4, 5], magnetism [6, 7, 8, 9], a superconductor-to-insulator transition [1, 4, 10] and a metal-to-insulator transition [11, 12]. Recently multiple groups have also reported the co-existence of superconductivity and magnetism in the same sample [1, 13]. This rare juxtaposition of two normally antagonistic phenomena provides the possibility of studying novel physics.

Details of the sample growth and fabrication have been discussed in earlier publications [1, 14]. As was shown previously, the system exhibits a superconductor-to-insulator transition as a function of gate voltage applied to the substrate [1]. It was also shown that the system has ferromagnetic order. Because of the existence of ferromagnetic order, a striking feature of any magnetoresistance measurement on this system is that it is hysteretic. Fig 1a shows the longitudinal magnetoresistance for $V_g = 20$ V at $T = 50$ mK; it is hysteretic at low fields. The magnetoresistance is saturates to $R \sim 1.5$ k at $H = 100$ mT, which sets the field scale for $H_{c2}$. This is borne out by the explicit measurement of $T_{cuv}H$ in [1]. The hysteresis is observed at a much lower field scale. The longitudinal resistance has been discussed in detail in Ref [1]. Here we will concentrate on the evolution of the transverse, i.e. the Hall, the magnetoresistance with gate voltage.
Fig 1b shows the Hall resistance as a function of the magnetic field at four different gate voltages $V_g = 20, -20, -60$ and $-100$ V at $T = 50$ mK. Before discussing the hysteretic low field behaviour of the Hall resistance, we look at the high field regime ($H > 300$ mT). It can be seen from Fig 1b that the Hall resistance at high fields is non-hysteretic and has a linear component at all gate voltages. One can extract the Hall slope $(R(H)/H)$ from the normal state ($T = 270$ mK) linear Hall resistivity of the system [1]. The evolution of the Hall slope with gate voltage in the normal state points towards the existence of multiple charge carriers in the system with a complex dependence of the density and mobility of the charge carriers on the gate voltage. At $T = 50$ mK the superconducting order parameter of the system has attained an appreciable value (for $V_g = 20$ V). However, the slope of the linear background at $T = 50$ mK at high magnetic fields is the same as that at $T = 270$ mK. This suggests that at high fields, the density and mobility of charge carriers in the system is identical to that at $T = 270$ mK, i.e. the system is in the normal state.

At low fields the Hall signal has a very unusual dependence on the field. For clarity, Fig 2 shows an expanded view of the low field region. Fig 2b is with the field swept from negative to positive values. Fig 2a shows that the Hall resistance for all the gate voltages is hysteretic, although the hysteresis is barely discernible for $V_g = -100$ V. The two dimensional conductor/superconductor not only sees the externally applied magnetic field but also an intrinsic hysteretic magnetic field due to the ferromagnet. To understand the effect of the combined external and internal fields on the system, let us first concentrate on $V_g = 20$ V, a gate voltage at which the system is superconducting. From Fig 2b it can be seen that the Hall resistance starts deviating from linear behaviour at $H \sim 100$ mT, close to $H_{c2}$ for this gate voltage [1].

In the mixed state of Type-II superconductors ($H_{c1} < H < H_{c2}$), an additional Hall resistivity superimposed on the normal state Hall resistivity results from the flux flow due to the movement of the superconducting vortices [15, 16]. The Hall signal results from the component of the vortex flow parallel to the transport current, $J_T$, or the superfluid velocity $v_s$ [17, 18, 19]. Below $H_{c1}$ or the vortex lattice melting field $B_m$, in the absence of mobile vortices, the longitudinal as well as the Hall resistance should vanish. This is indeed confirmed by a decrease in the Hall resistance below $H \sim 25$ mT. However, on crossing zero when sweeping from negative to
positive fields, (i.e. at a very small positive field) there is a sharp jump in the Hall resistance, indicated by the little arrow in Fig 2b. This sharp feature is caused because of the presence of the ferromagnet. As the externally applied magnetic field passes through zero and attains a certain value a domain wall is nucleated in the ferromagnet. As soon as a domain wall is nucleated, it propagates through the ferromagnet. This domain wall nucleating field is close to the coercive field of the ferromagnet. The domain wall motion results in a large flux flow through the superconductor. The proximity of the ferromagnet to the superconductor causes a very large local magnetic field at the superconductor and hence a large number of vortices. It is this combination of fast flux flow coupled with the large number of vortices that gives rise to the sharp increase in the Hall signal at a small field value ($H \sim 10 \text{ mT}$). The nucleation and propagation of a domain wall causes the magnetization reversal in the ferromagnet. Once the magnetization has switched, the system relaxes back to its normal behaviour.

Now we turn to analysing the gate voltage dependence of the Hall resistance as the system is tuned through a superconductor-to-insulator transition. The gate voltage at which this transition occurs is $V_g \sim -30 \text{ V}$. For $V_g = -20 \text{ V}$, a gate voltage at which there still exists some superconductivity in the system [1], the Hall features are similar to that at $V_g = 20 \text{ V}$, but at a lower field. This is due to the lower $H_{c2}$ for $V_g = -20 \text{ V}$. On decreasing the gate voltage beyond $-30 \text{ V}$, the system enters the insulating state, i.e. the resistance does not decrease with decreasing temperature; instead, it increases. The behaviour of the Hall resistance in this regime gives insight into the nature of the insulating state. The effect of decreasing gate voltage is to decrease the density of charge carriers at the interface. One might ask if this low density gas has superconducting coherence at all? If there were no superconductivity at all, the Hall resistance would be linear for all fields and there would be no non-linear component in it. However, when one examines the Hall resistance for $V_g = -60 \text{ V}$, one sees a small but finite non-linear component in it near zero field. At $V_g = -100 \text{ V}$ a non-linear Hall signal is barely observed. This suggests that in the insulating regime, superconductivity is not completely destroyed; instead increasingly localized superconducting islands are formed connected to each other through in-
sulating regions. The superconducting islands are still large enough to sustain flux flow due to vortex motion and hence giving rise to a non-linear Hall resistance.

In conclusion, the Hall slope \((R(H)/H)\) at \(T = 50\) mK at high magnetic fields matches that at \(T = 270\) mK (normal state). This implies that the nature of charge carriers (density and mobility) is the same at low temperatures. However, in the low field region one sees a non-linear and hysteretic Hall resistance. For the superconducting state \((V_g = 20, -20\) V\) this is due to the flux flow motion. For the insulating gate voltages also, however, the Hall resistance is non-linear and hysteretic, though the non-linearity is smaller. This is due to the localized superconducting islands in the system, although further evidence is needed to establish this. The intrinsic field of the ferromagnet induces vortices in the system, in addition to those induced by the externally applied field. The sharp features in the Hall resistance are the result of domain wall motion at the time of magnetization reversal.

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