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We present a study of the magnetic field tuned superconductor-to-insulator transition (SIT) in the electron gas that forms at the $LaAlO_3$/$SrTiO_3$ interface. We find that the magnetic field induces a transition into a weakly insulating state, as is observed for the electrostatically tuned SIT at this interface. Finite size scaling of the magnetoresistance yields the critical exponent product $z\nu \simeq 7/3$, indicating that the transition is governed by quantum percolation effects. While such critical exponents have been reported previously for high resistance films, they have not been reported for a low resistance system like ours, with a maximum sheet resistance of ≈ 1.5 kΩ, much less than the quantum of resistance $R_Q \equiv h/4e^2 = 6.45$ kΩ.

Two dimensional superconductors are known to undergo a superconductor-to-insulator transition (SIT) upon varying an external parameter like disorder or magnetic field [1, 2]. This SIT is one of the most widely studied experimental realizations of a quantum phase transition (QPT) [3–7]. Many diverse 2D superconductors have been the subject of experimental studies of this SIT, among them are thin films of Bi [3], InO_x [4], and MoGe [5]; Josephson junction arrays [8]; various cuprate superconductors [9, 10], and more recently two dimensional superconducting interfaces between insulating oxides [11]. For all the diversity of these superconducting systems, the underlying electron system is believed to transition into an insulating state beyond a certain critical value of the external tuning parameter. Two possible scenarios for the nature of this insulating state have been proposed: (i) the system is a Bose insulator, characterized by localized Cooper pairs with a non-zero pair amplitude [1, 2]; or (ii) the system is a Fermi insulator, characterized by localized electrons and a vanishing pair amplitude [12]. Experimentally this transition has been studied on a variety of thin superconducting films prepared from different materials [3–7]. One of the observed characteristic signatures of the phase transition is the fan shaped curves of the temperature dependence of resistance, as a function of the disorder or the magnetic field, marking the transition from a zero resistance superconducting state to a high resistance insulating state. However, the strength and nature of the insulating state are different for different materials, and there is still debate about the universality of this transition as predicted by theory.

At finite temperatures T, one of the ways in which the SIT is studied is through the scaling of the resistance of the system with magnetic field H near a critical point. According to theory, the resistance takes the scaling form [2],

$$R(H,T) = R_C f[(H - H_C)/T^{1/z\nu}] \quad (1)$$

where f is a function of H and T. Here H_C is the critical field at which the transition occurs, z is the dynamical critical exponent, ν is the correlation length exponent, and R_C is a constant. Near the transition, the physics is governed by the competition between two length scales, the quantum fluctuations correlation length, $\xi \sim |H - H_C|^{-\nu}$, and a thermal length, $L_T \propto T^{1/z}$. The thermal length L_T is the length scale at which the quantum fluctuations at finite frequency $\hbar\Omega$ are cut off by the temperature $k_B T$. The resistance is some universal function of the ratio of these two length scales, giving rise to the scaling form above. Such scaling behaviour is a strong indicator of the occurrence of a phase transition, especially in the case of a continuous QPT, with the values of the critical exponents determining the universality class of the transition.

Here we report measurements of the perpendicular magnetic field tuned SIT that occurs in the two dimensional electron gas (2DEG) which forms at the interface between the two band insulators $LaAlO_3$ (LAO) and $SrTiO_3$ (STO) [13]. It has been shown previously that this system can be tuned through a SIT on the application of a gate voltage V_g [16, 19], which has the effect of changing the carrier density at the interface. Electrical transport measurements reported by various groups so far suggest that the system transitions into a weakly insulating state as a result of the applied V_g [16–19]. In this paper, we study the effect of a magnetic field on this system at various V_gs at which the system is superconducting, with the normal-state sheet resistance of the 2DEG varying from $R_\square^N \approx 800$ Ω to $R_\square^N \approx 1500$ Ω for the range of measured V_gs. We find a similar weakly insulating state in the magnetic field-tuned transition at this interface. The resistance scales with H and T in accordance with Eq. (1) with the critical exponent

product $z\nu = 7/3$ giving the best scaling of the magnetoresistance (MR) data for all V_gs. This indicates that quantum percolation effects dominate transport at the transition [20]. The system can be modeled as a network of superconducting grains (gap, $\Delta > 0$) embedded in a non-superconducting material ($\Delta = 0$) with strong $e - e$ interactions. This model is supported by the growing evidence for local inhomogeneity at the interface [17, 21, 23].

In addition to superconductivity, this system also shows signature of ferromagnetism that coexists with the superconductivity [16, 21, 22], where the ferromagnetic moment lies in the plane of the 2DEG [21, 24]. Due to the effect of the magnetization dynamics of the ferromagnet, the magnetoresistance of the system is hysteretic [16, 17]. In order to study the magnetic field-tuned transition at the interface, we have chosen to eliminate the effect of hysteresis due to the ferromagnet on the 2DEG by applying a small parallel field, $H_\parallel = 100$ mT that aligns the moment of the ferromagnet in one direction. The sample growth and electrical transport properties have been discussed in earlier publications [14–17]. The electrical transport measurements of the sample were made using a standard a.c. lockin technique, with an excitation current of 19.2 nA and a frequency of 22.6 Hz in a dilution refrigerator.

Each panel in Fig. 1 shows the MR of the system at four temperatures below the measured transition temperature T_C of the sample, where we define T_C as the midpoint of the resistive transition. The three panels show the MR for three different V_gs at which the system is superconducting. Due to the application of a constant parallel field, the MR is non-hysteretic. Hence, we show data for one sweep direction of $H_\perp$ ($H_\perp$ swept from $0 \rightarrow 320$ mT). (The parallel field also results in a small (~ 3 mT) asymmetry about $H_\perp = 0$ mT due to the misalignment of the sample in the field.) In these samples, the maximum T_C occurs at $V_g = 60$ V, with the T_C decreasing upon further reduction of V_g. For all V_gs, the system reaches a state of higher resistance with a weak temperature dependence upon the application of magnetic field. It has been argued by us [17] and others [18] that the nature of the insulating state in the gate voltage tuned SIT can be described by taking into account the $e - e$ interactions in the electron gas. This picture describes the observed weak temperature dependence of the resistance in the electrostatically tuned SIT. An obvious question arises about the nature and strength of the insulating state in the magnetic field tuned transition, which we address below.

It is seen from Fig. 1 that beyond a certain critical field (which is roughly the field at which the different MR isotherms cross; more on the determination of the critical field below) the MR increases slowly with the field at all temperatures for all the V_gs. Unlike more resistive systems in which the field-tuned transition is studied [7, 25, 26], we do not observe a large peak in the
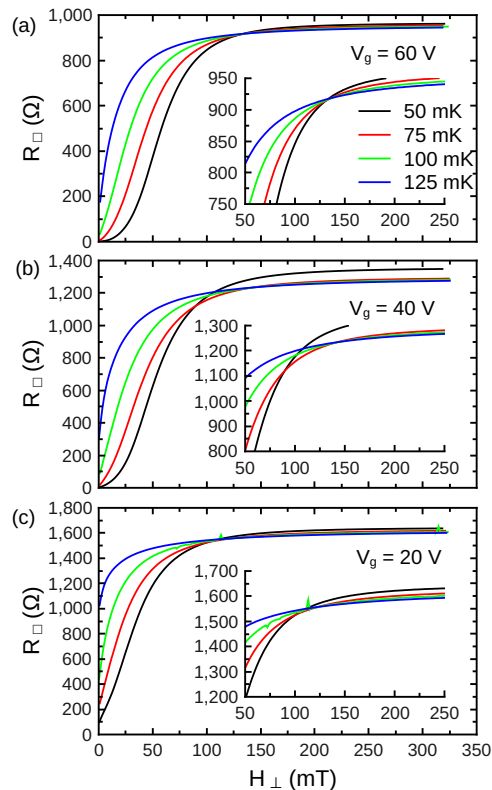

FIG. 1. (a), (b), and (c) are the MR at four different temperatures for the three different V_gs, $V_g = 60$ V, 40 V, and 20 V respectively, in order of decreasing T_Cs. The insets show the zoomed in region of the MR where the different isotherms cross each other.

MR, at least in the measured field range. This peak in MR is believed to arise due to the localization of Cooper pairs in the insulating state, with the size of the peak increasing with decreasing temperature. The origin of the peak can be ascribed to the difficulty of Cooper pair tunneling between neighbouring superconducting grains due to the phase randomization between them in an increasing magnetic field. An observation of the MR peak is one of the signatures of the system being in the so-called Bose insulator phase. The fact that we do not observe this peak, coupled with the relatively small temperature dependence of the MR might suggest that the insulating state reached in the field tuned transition is dominated by Fermion physics, i.e., that the superconducting gap is uniformly destroyed throughout the sample and that the transition is more like a superconductor-to-metal transition. However, as mentioned above, the weakly insulating regime in the gate tuned SIT can be explained by the $e - e$ interactions in the system, and the distinction, if any, between a *metal* with strong $e - e$ interactions and a weak insulator is difficult to resolve through the MR data. One therefore needs to perform a scaling analysis of the SIT, and from the critical exponents extracted, more can be said about the nature of the transition, as
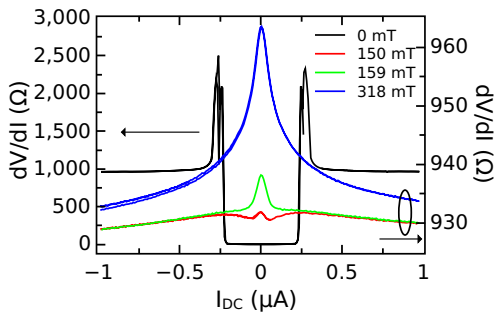
FIG. 2. The magnetic field induces a transition into a weakly insulating state as seen for $V_g = 60$ V here. The transition happens close to $H_\perp = 159$ mT. $T = 50$ mK.

we show below.

In order to verify that the magnetic field does indeed cause a transition to a weakly insulating state, we have measured the differential resistance of the sample as a function of applied dc current I_{dc} at various discrete magnetic fields. This is shown in Fig. 2 for $V_g = 60$ V and $T = 50$ mK. As the field is increased, the system transitions from a superconducting to an insulating regime, as seen by the disappearance of the two dips in resistance at low bias between $H = 150$ mT and $H = 159$ mT. For the highest measured field, $H_\perp = 318$ mT, the fractional change in resistance between $I_{dc} = 0$ μA and $I_{dc} = 1$ μA is ~ 3.2 %. A similar change of resistance is observed in the insulating state reached by the gate voltage tuned transition [17, 18].

As discussed above, one of the ways in which the field tuned transition is analyzed is through the universal scaling behaviour of some physical property of the sample, such as resistance. A critical factor determining the successful scaling of experimental data is the determination of the critical field H_C. One way to determine H_C is to see at what field the various MR isotherms cross (Fig. 1). However, this does not give an accurate measure of H_C. From Fig. 2 it can be seen that the transition happens close to $H_\perp = 159$ mT for $V_g = 60$ V. However, the determination of H_C by changing the field in discrete steps is a very time consuming process, particularly for a system with such a large phase space.

To ascertain the value of H_C for the different V_gs in the superconducting regime, we have measured the third derivative of voltage with current, d^3V/dI^3, as a function of the field. The advantage of this technique is that it is much faster to observe the field tuned transition compared to measuring the R vs. T or I-V characteristics at discrete magnetic fields. When the system is not dc biased (i.e. $I_{dc} = 0$), $dV/dI = 0$ in the superconducting state, and it is positive and a maximum in the insulating state (Fig. 2). Thus, it can be seen that $d^2V/dI^2 = 0$ in both the superconducting and the insulating states. However, the third derivative, $d^3V/dI^3 \geq 0$ in the superconducting regime, whereas $d^3V/dI^3 < 0$ in the insulat-

ing regime. Therefore, the value of $H_\perp$ at which d^3V/dI^3 changes sign from positive to negative is the critical field H_C.

Figure 3 shows d^3V/dI^3 vs $H_\perp$ for three different V_gs at which the system is superconducting at zero field. Some non-monotonic features are seen at low fields, which arise due to the curvature in the shape of the MR (Fig. 1). As expected, the system transitions into the insulating state for all V_gs at higher fields, as seen by the change in sign of the curves, and the critical fields are different for different V_gs. For $V_g = 60$ V, $H_C = 159$ mT, indicated by the arrow. This value of H_C is confirmed by the measurements displayed in Fig. 2, where precisely at $H = 159$ mT one sees the change from superconducting to insulating behaviour. Figure 3b shows the dependence of H_C on the measured transition temperature, T_C, for the different V_gs. It was argued by Fisher [2] and demonstrated by Hebard and Paalanen [4], that near the critical point of the disorder driven transition, $H_C \sim T_C^{2/z}$. We do not see such behaviour in our data, but that could be because at the measured V_gs our system is still relatively far from the SIT occurring in the gate voltage tuned transition.

With the values of H_C extracted from the d^3V/dI^3 measurements one can proceed to the scaling analysis of the MR data. This is shown in Fig. 4 for the different V_gs. The MR data are reasonably well scaled for the measured range of temperatures. The critical exponent product that best scales the data is $z\nu = 7/3$, which is ex-
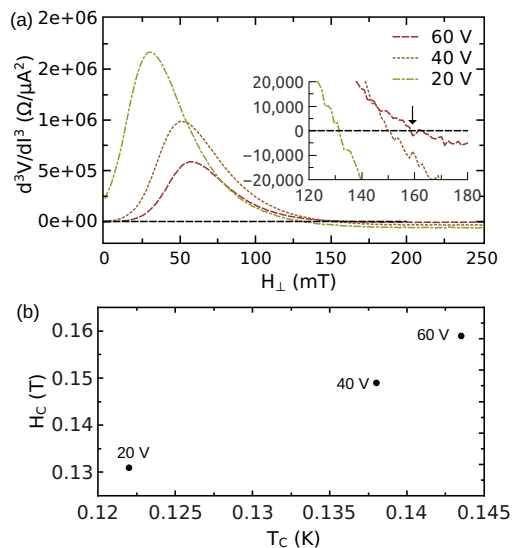

FIG. 3. (a) d^3V/dI^3 vs $H_\perp$ for different V_gs. The horizontal dashed line indicates the zero of d^3V/dI^3. When the third derivative crosses this line as a function of the field, the system passes into an insulating state. The inset shows the zoomed in region of the zero crossings for the three V_gs. The critical value of the field for $V_g = 60$ V is indicated by the arrow, $H_C = 159$ mT. $T = 50$ mK. (b) Measured H_C as a function of measured T_Cs for the different V_gs.
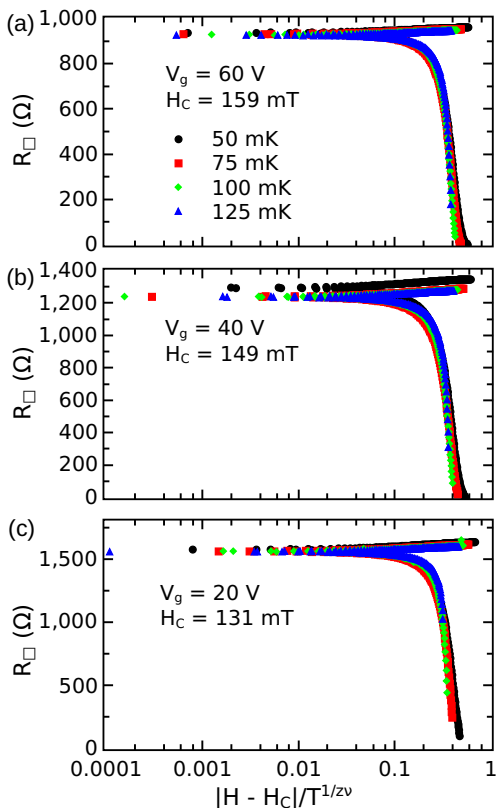
FIG. 4. $R_\square$ vs $|H - H_C|/T^{1/z\nu}$ for (a) $V_g = 60$ V, (b) $V_g = 40$ V, and (c) $V_g = 20$ V. The critical exponent product $z\nu = 7/3$ best fits the data, such that visually all the curves collapse onto each other.

pected where quantum percolation is dominant [20, 27]. For inhomogeneous systems that show a phase transition from a conducting to a non-conducting state, quantum percolation signifies transport through charge tunneling (as opposed to direct transport) between two conducting regions across a non-conducting region. In the 2D SIT, the question is whether the principal charge transport is through Cooper pairs (Bosons) or through electrons (Fermions) as the magnetic field is increased. Previous studies [4, 5] of the magnetic field tuned SIT in thin film superconductors have yielded the critical exponent product $z\nu = 4/3$, which corresponds to transport through classical percolation. Usually this critical exponent product has been seen for films with a wide range of normal state resistances. For example, Hebard et $al.$ [4] report a transition for InO_x films with $R_\square^N \sim 6$ kΩ, whereas Yazdani et $al.$ [5] report a transition in $\alpha-$MOGe films with $R_\square^N \lesssim 2$ kΩ. On the other hand, the critical exponent product $z\nu = 7/3$ has been reported for high resistance InO_x films by Steiner et $al.$ [27]. In contrast, our data shows a transition based on quantum percolation ($z\nu = 7/3$) for a relatively low resistance system (maximum $R_\square^N \approx 1.5$ kΩ at $V_g = 20$ V). Using this fact, we argue below that the field tuned SIT in this system is

Bosonic, i.e., governed by Cooper pair transport on the insulating side.

Given that our samples have low disorder ($k_F l \approx 19$, where k_F is the Fermi wave vector and l is the elastic mean free path), it is unlikely that electrons would be localized on isolated grains in the weakly insulating regime. If the dominant carriers were Cooper pairs, however, one could imagine the Cooper pairs localized on superconducting islands, isolated from Cooper pairs on other islands by intervening normal regions, with the principal transport mechanism being tunneling of Cooper pairs from one island to another. Consequently, the dominant charge transport at the transition occurs through Cooper pair tunneling, implying that even on the insulating side, Cooper pairs and hence the superconducting order parameter survive locally while global phase coherence is lost. A more local probe of the superconducting phase correlations would help shed more light on the matter.

In conclusion, we have measured the magnetic field induced SIT at the LAO/STO interface. As seen in the electrostatically tuned transition at this interface, the magnetic field also causes the system to transition into a weakly insulating state, characterized by a weak temperature dependence of the MR. The critical exponents obtained from the scaling of the MR data indicate that quantum percolation effects govern the physics at this transition, signifying Cooper pair tunneling contributes to the transport on the insulating side.

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