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Magnetic-field induced metal-insulator transition in $\text{SrTiO}_{3-\delta}$

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Abstract

Metallic samples of $\text{SrTiO}_{3-\delta}$ with charge-carrier densities of $n = 8.6 \times 10^{16} \text{ cm}^{-3}$ and $2.0 \times 10^{17} \text{ cm}^{-3}$ are shown to exhibit magnetic-field-induced metal–insulator transitions. Landau levels emerge in the magnetic field, and their energy spacing is comparable to the Fermi and thermal energies. A simple parallel-conduction model involving thermally-activated hopping among Landau levels is introduced to describe the data below the metal–insulator transition temperature.

Keywords: magnetoresistivity, metal–insulator transitions, Landau levels, semiconductors

1. Introduction

SrTiO_3 is a semiconductor whose mobile charge-carrier density can be altered through the creation of oxygen-vacancies, donor-doping with Nb [1] or La [2], and electrostatic gate control [3]. Its electrical resistivity varies dramatically with the charge-carrier density n , which can range from 10^{15} to 10^{20} cm^{-3} [4–6], while exhibiting an extremely high charge-carrier mobility [7]. Metallicity develops near $n \sim 10^{17} \text{ cm}^{-3}$ and superconductivity ($T_c < 0.5 \text{ K}$) arises when $n \sim 10^{18} \text{ cm}^{-3}$ [1], the latter value of n corresponds to an average intercarrier distance of about 120 Å ($\sim 1/n^{1/3}$), and Fermi energy $E_F \sim 3.6 \text{ meV}$ ($T_F \sim 42 \text{ K}$). The coherence length for its superconducting electrons is $\sim 100\text{--}1000 \text{ Å}$ [8, 9], comparable to the average intercarrier spacing.

It is interesting to compare SrTiO_3 with n near the region where metallicity develops ($n \sim 10^{17} \text{ cm}^{-3}$) to a conventional metal. Its electrons would have an intercarrier spacing of about 260 Å instead of 3 Å . The corresponding average electrostatic energies due to Coulomb repulsion would be 0.05 eV and 4.8 eV . The Fermi energies according to the free-electron model would be $\sim 0.8 \text{ meV}$, corresponding to a Fermi temperature $T_F \sim 9 \text{ K}$, and $\sim 8 \text{ eV}$ ($T_F \sim 91\,000 \text{ K}$), respectively. Thus, the Fermi distribution is extremely broad and it is possible to think of $\text{SrTiO}_{3-\delta}$ as a metal with electrons that are semi-classical, even at liquid helium temperatures. Investigation of the response of electrons to magnetic field in this environment offers the possibility to study a quantum regime not accessible in conventional metals.

In this report, single crystals of $\text{SrTiO}_{3-\delta}$ with values of $n = 8.6 \times 10^{16} \text{ cm}^{-3}$ and $2.0 \times 10^{17} \text{ cm}^{-3}$ are investigated. They are slightly below the lower boundary of the superconducting regime [1]. The crystals exhibit metal-like electrical resistivity ρ in zero magnetic field and have Fermi energies E_F estimated at 0.39 and 0.69 meV , respectively, taking into account the effective electron mass of $m = 1.8m_e$ [7]. With the definition of $d\rho/dT$ positive as metal-like and $d\rho/dT$ negative as insulator-like behaviors, magnetic field H , which is perpendicular to the

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electrical current, causes a change in $d\rho/dT$ from positive to negative, revealing a metal–insulator transition. A critical field H_c separates the metal-like and insulator-like regimes. The observed behavior is attributed to the formation of cyclotron orbits and the associated quantized Landau levels.

The energy spacing between each Landau level is $\hbar\omega_c$, where $\hbar$ is Planck's constant divided by 2π and $\omega_c = eH/m$; e is the electron charge and m is the effective electron mass. E_F , $\hbar\omega_c$, and $k_B T$ are of similar magnitude in the magnetic field, temperature, and charge-carrier concentration ranges of this study, placing our experiments in an interesting quantum regime (k_B is the Boltzmann constant). In this environment, magnetic field reduces the Landau-level orbit diameter below the average spacing of the charge carriers, leading to localization. Hopping between Landau energy levels results in thermally-activated conduction and an elevated number of Landau levels are accessible due to the very broad Fermi distribution. An empirical model involving parallel resistors [10] represents the data well and may provide insight into the magnetic-field-induced localization of electrons in other systems such as the doped semiconductors [11] Si [12], InSb [13], GaSb [14], InAs [15], GaAs [16], which have values of n comparable to the specimens studied herein.

2. Experimental details

Two high-quality single crystals from Macashew technologies (Sample 1: $5.00 \times 1.75 \times 0.50$ mm³ and Sample 2: $5.00 \times 1.50 \times 0.50$ mm³) were reduced at 715 °C (Sample 1) and 725 °C (Sample 2) for 5 h in a furnace under a dynamic vacuum of $\sim 5 \times 10^{-6}$ mbar. Due to the growth habit, the thin axis of both crystals is parallel a principal crystallographic axis of the room temperature cubic structure; the crystals were otherwise not oriented. Gold pads were evaporated onto the samples for 4-probe dc electrical resistivity and 5-probe ac Hall effect measurements using a Quantum Design PPMS. Typical contact resistances were below 80 Ω . I-V curves at room temperature and 5 K revealed linear behavior for both specimens. The charge-carrier densities n were determined using Hall effect measurements at room temperature, ramping the current from -1 mA to $+1$ mA, in a magnetic field of 3 tesla (see figure 1(a)). The variation of n with temperature is shown in figure 1(b). The room temperature electrical resistivities ρ (295 K) with corresponding room temperature n values are ~ 14.5 Ω cm with 8.6×10^{16} cm⁻³ (Sample 1), and ~ 6 Ω cm with 2.0×10^{17} cm⁻³ (Sample 2), which compare well with those of prior studies [4, 17, 18]. The current densities used for the $\rho(T)$ measurements were 114 mA cm⁻² for the $n = 8.6 \times 10^{16}$ cm⁻³ specimen and 7 mA cm⁻² for the $n = 2.0 \times 10^{17}$ cm⁻³ specimen. Current was applied in the plane of the platelet-shaped crystals and the field was perpendicular to that plane (inset of figure 2(b)). A small amount of grease was used to assure thermal contact between the samples and the massive copper measurement platform. Although the PPMS, its wiring to the sample, and the electronics are electrically shielded,

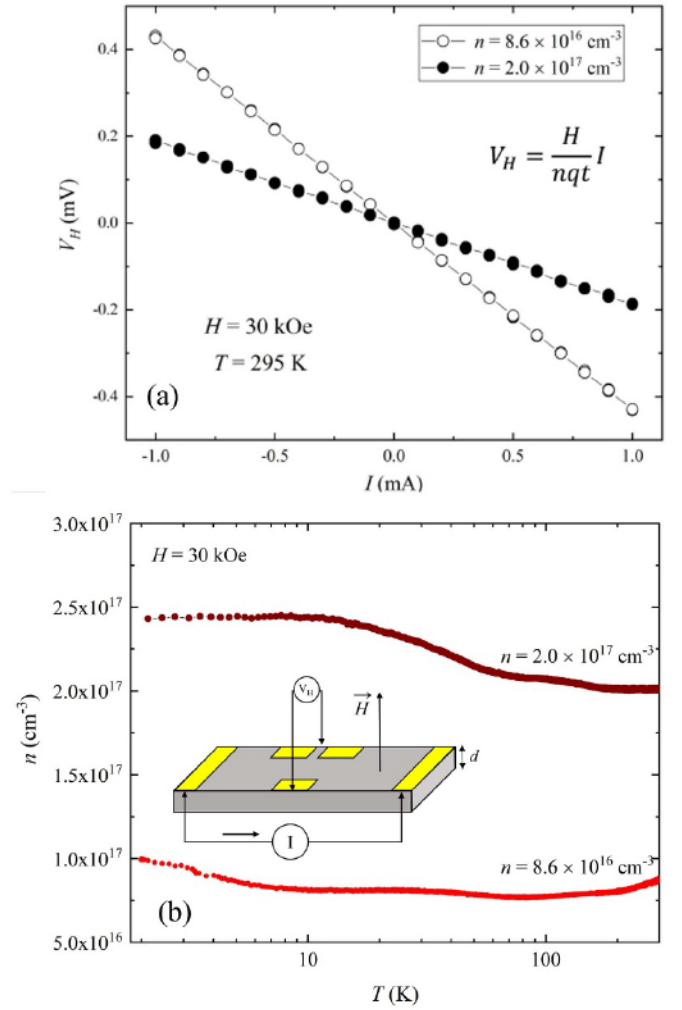


Figure 1. (a) Hall voltage $V_{Hall} = IH/nqt$ obtained at constant field $H = 30$ kOe while ramping the current I at 295 K. Sample thickness was $t = 0.50$ mm, q is the electron charge. (b) Charge carrier concentration n versus temperature. Inset illustrates the measurement geometry.

a spectrum analyzer was employed to test the measurement chamber for electrical noise from 0 to 100 kHz. A few random frequencies exhibited spurious noise levels as high as $5 \mu V_{rms}$. The continuous noise level was about 50 times smaller than this. Based on the sample contact resistance, the maximum heating this could amount to is ~ 0.3 pW, which is negligible in the temperature range (1.8 K to 30 K) of this study.

3. Results

The electrical resistivity ρ versus temperature T data shown in figure 2(a) reveal that the specimens are very close to the boundary where $SrTiO_{3-\delta}$ exhibits either metal-like or insulator-like behaviors at the temperatures of this study. Our observed values of $n = 8.6 \times 10^{16}$ cm⁻³ and 2.0×10^{17} cm⁻³, and the associated $\rho(T)$ behaviors compare well with published data [1, 4, 19], placing the specimens at the under-doped

border of T_c versus n [1]. They are close to the doping region ($3.6 \times 10^{17} \text{ cm}^{-3}$ to $12 \times 10^{17} \text{ cm}^{-3}$) where the Shubnikov-de Haas effect [20] was observed below $\sim 2 \text{ K}$ in thin-film $\text{SrTiO}_{3-\delta}$; oscillations in the Nernst effect were observed [21] for n as small as $5.5 \times 10^{17} \text{ cm}^{-3}$.

Figures 2(b) and (c) show $\rho(T)$ curves obtained under dc magnetic fields ranging from 0 to 90 kOe. A metal-insulator transition is clearly observed in both specimens. The curves acquired at 7.5 kOe and 15 kOe for $n = 8.6 \times 10^{16} \text{ cm}^{-3}$ and $2.0 \times 10^{17} \text{ cm}^{-3}$, respectively, reveal nearly temperature-independent behavior of ρ below $\sim 6 \text{ K}$ (see the black curves, insets of figures 2(b) and (c)).

It is worth mentioning additional measurements carried out on specimens with $n = 1.6 \times 10^{16} \text{ cm}^{-3}$ and $4.0 \times 10^{18} \text{ cm}^{-3}$. In the case of $n = 1.6 \times 10^{16} \text{ cm}^{-3}$, insulator-like behavior occurs below 15 K with $H = 0$, and magnetic field has the effect of increasing ρ . For $n = 4.0 \times 10^{18} \text{ cm}^{-3}$, metal-like behavior occurs to the lowest measured T , and magnetic field has the effect of increasing ρ , but our apparatus is unable to attain the magnetic field intensity required to result in $d\rho/dT < 0$. Notably, the trends are similar to those exhibited in figure 2.

To better characterize the magnetic-field-induced metal-insulator transition, ρ was measured at fixed temperatures while varying the magnetic field. Figure 3(a) shows the obtained magnetoresistance (MR) data. In the case of $n = 8.6 \times 10^{16} \text{ cm}^{-3}$, a distinct crossover point is evident at approximately $\rho(7.8 \text{ kOe}) \approx 7.5 \text{ m}\Omega \text{ cm}$. Similarly, for $n = 2.0 \times 10^{17} \text{ cm}^{-3}$ a distinct crossover point is evident at $\rho(15 \text{ kOe}) \approx 4.3 \text{ m}\Omega \text{ cm}$ (see figure 3(b)). Thus, the magnetic fields $H_c = 7.8 \text{ kOe}$ and 15 kOe are identified as the crossover fields from metal- to insulator-like behavior.

The insets of figure 3 show the MR plotted as $\rho(H)/\rho(H=0)$ versus H for both samples. Notable is the magnitude of the MR, which reaches many times $\rho(H=0)$ at the lowest temperatures and 9 tesla. For normal metals, only a few percent increase, $\rho(H) \sim H^2$ at low fields, and a saturation in high fields are expected [22], none of which applies to the data in figure 3. The observations suggest that the proximity of these $\text{SrTiO}_{3-\delta}$ specimens to the metal-insulator transition plays a dominant role in the MR.

4. Magnetic-field induced charge-carrier localization

For the geometry considered herein, with current in the x - y plane and magnetic field H along z , the charge carriers enter cyclotron orbits, unless their momenta are restricted to z . According to quantum mechanics [22–24], the electrons in these orbits have energies $E_a = (a + 1/2)\hbar\omega_c + (\hbar^2/2m)k_z^2$, these quantized orbits are known as Landau levels. Here $\omega_c = eH/m$ is the cyclotron frequency for an electron of charge e in magnetic field H with effective mass m , a is the quantum number ($a = 0, 1, 2, \dots$), and $\hbar k_z$ is the momentum parallel to H . The effective mass $1.8m_e$ [7, 26] is used below. As magnetic field penetrates the sample, the field does no

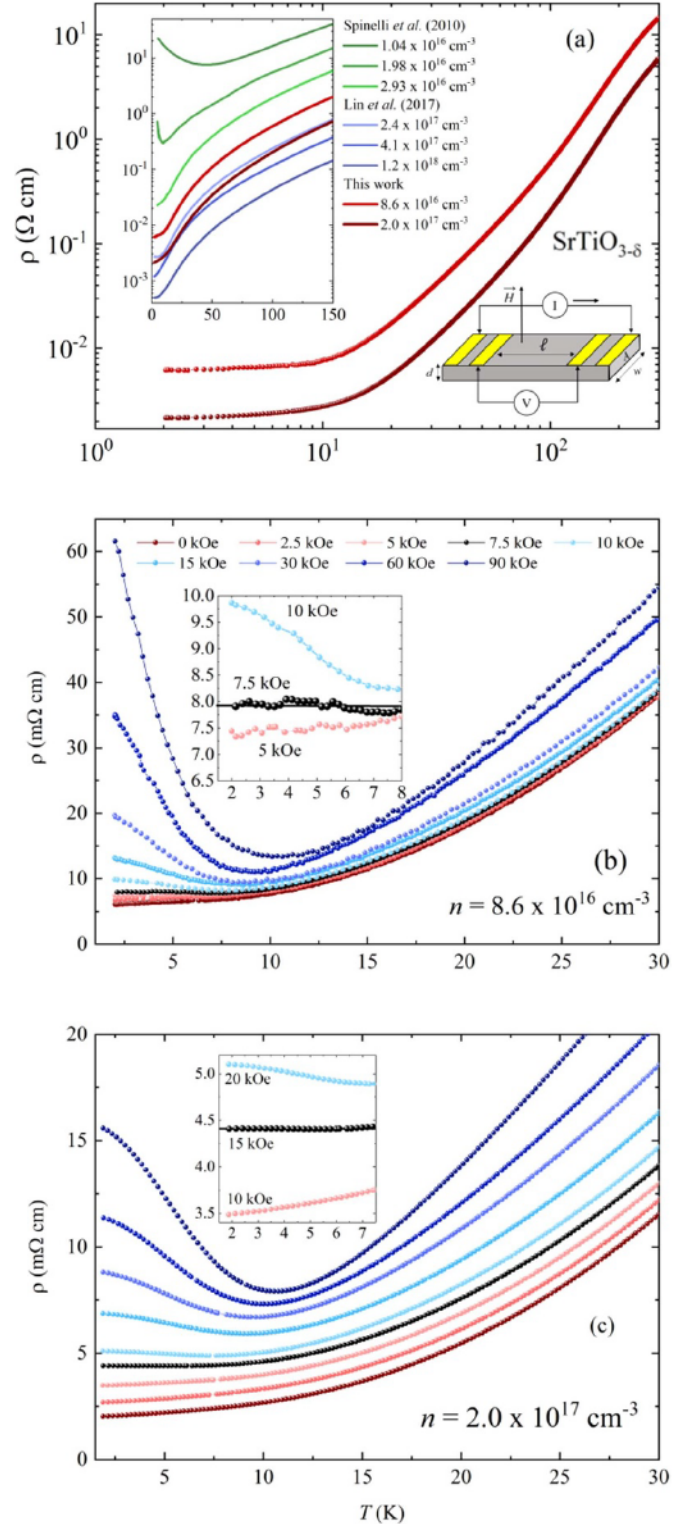


Figure 2. (a) (main panel) Electrical resistivity $\rho(T)$ of $\text{SrTiO}_{3-\delta}$ single crystals with $n = 8.6 \times 10^{16} \text{ cm}^{-3}$ and $2.0 \times 10^{17} \text{ cm}^{-3}$. The data are compared to published results [1, 4, 19] in the left inset. The right inset illustrates the measurement geometry. (b) $\rho(T)$ curves for the specimen with $n = 8.6 \times 10^{16} \text{ cm}^{-3}$; the region near the crossover from metal- to insulator-like behavior is shown in the inset. (c) $\rho(T)$ curves obtained for the specimen with $n = 2.0 \times 10^{17} \text{ cm}^{-3}$; the region near the crossover from metal to insulator-like behavior is shown in the inset.

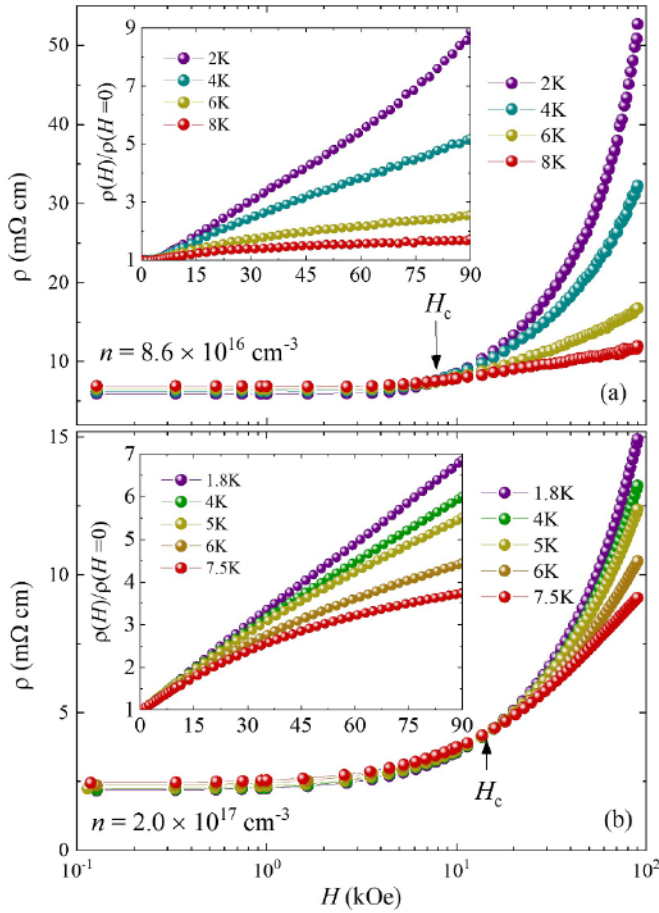


Figure 3. Magnetoresistance isotherms for the ranges 1.8 to 7.5 K and 0 to 90 kOe for the $\text{SrTiO}_{3-\delta}$ single crystals with $n = 8.6 \times 10^{16} \text{ cm}^{-3}$ and $2.0 \times 10^{17} \text{ cm}^{-3}$. The magnetic field H_c , which is the crossover field from metal to insulator-like behavior is indicated in each figure.

work on the electrons and their total average energy remains unaltered. Since the magnetic field is along z , the average momentum of the electrons in the z direction, $\hbar k_z$, is unaltered. Their average momentum magnitude in the x and y direction is also unchanged. The electrons are in quantized orbits in the k_x – k_y plane, condensing onto the nearest orbit [22]. In a purely two-dimensional system, the electrons may occupy the same Landau energy level up to a maximum number $D' = 2\Phi/\Phi_0$, where Φ is the magnetic flux, $\Phi_0 = h/e$ is the magnetic flux quantum [22–24], and the factor of 2 allows for double occupancy of each orbit. In our three-dimensional case, $D \approx D' \times tn^{1/3}$, would be the maximum number of electrons in the same Landau energy level, t is the sample thickness and $n^{-1/3}$ is the approximate spacing between charge carriers. Thus, the addition of H modifies the energy spectrum dramatically, and forces many electrons into identical energy levels. However, the total number of states associated with a given volume of k space is unchanged [22].

Using the volume of each sample and the respective n values, we find 3.8×10^{14} and 7.5×10^{14} charge carriers in

samples 1 and 2, respectively. The obtained estimates for D at 9 tesla are 7.6×10^{14} and 1.0×10^{15} , respectively. Thus, all charge carriers can be accommodated in the lowest Landau energy level at 9 tesla. Since the Fermi energies for samples 1 and 2 are 0.39 and 0.69 meV, respectively, and the ground state energy $E_0 = (1/2)\hbar\omega_c \approx 0.29$ meV at 9 tesla, all charge carriers are below E_F . In general, the total number of states that are available is approximately $DE_F/(\hbar\omega_c)$, which is independent of H . Thus, at lower magnetic fields, while there are more Landau levels with energies below E_F , the number of charge carriers that can be accommodated remains unaltered. Notable is the discreteness of the energy levels. As an example, for sample 2, while there is only one Landau level below E_F at 9 tesla, there are eight at 1 tesla. In contrast, for a common metal such as copper with $n \sim 10^{23} \text{ cm}^{-3}$ and a Fermi energy of ~ 7 eV, there are about 6700 Landau energy levels below E_F at 9 tesla and over 60 000 at 1 tesla.

$\text{SrTiO}_{3-\delta}$ is a doped semiconductor with a large dielectric constant of $\epsilon \sim 20\,000$ in its pristine state [25] in the temperature range of the present study. In this environment, the doped charge carriers possess effective Bohr radii of $a_B \sim 6000 \text{ \AA}$ [7, 26]. Along with the large Bohr radius, the corresponding binding energy is extremely small ($\sim 10^{-8}$ eV), so the charge carriers are delocalized. As the charge carriers enter cyclotron orbits in the plane perpendicular to H (the x - y plane), the radii of these orbits is [11] $r_t \sim (\hbar/eH)^{1/2}$. With this in mind, the probability that neighboring charge-carrier orbits overlap in the x - y plane will decrease significantly when $r_t \lesssim n^{-1/3}$. That is, above a certain magnetic field magnitude one would expect the charge carriers to exhibit signs of localization for transport perpendicular to H . For the two specimens in this study, values of 13 kOe and 22 kOe are estimated for $n = 8.6 \times 10^{16} \text{ cm}^{-3}$ and $n = 2.0 \times 10^{17} \text{ cm}^{-3}$, respectively, which are about twice the observed H_c values. The discrepancy can likely be traced to the argument's simplicity. In contrast, for copper with a charge carrier spacing of a few $\text{\AA}$, localization would be unexpected for magnetic fields below ~ 7000 tesla.

As noted above, with the magnetic field along z , the charge carriers are in quantized orbits in the k_x – k_y plane. The allowable orbits have an energy spacing of $\hbar\omega_c$. The Zeeman effect splits each of those levels, but the energy spacing remains $\hbar\omega_c$. Since $\hbar\omega_c$ is proportional to H , the energy spacing increases with H and the number of energy levels below E_F decreases with increasing H . Evident in figures 2 and 3 is that the MR grows with H . The discrete nature of the energy levels, the field-induced localization of the charge carriers, and the increase in spacing between energy levels as H is increased led us to the hypothesis that the electrical resistivity might obey $\rho(T) \sim e^{\Delta E/k_B T}$, where $\Delta E \propto \hbar\omega_c$.

The data were plotted as $\ln \rho$ versus $1/T$ in order to test the hypothesis (figure 4). There is a narrow region immediately below $T_{\min}$ that could be fitted to a straight line, which yielded good agreement with $\Delta E \sim \hbar\omega_c$. However, the behavior at lower T is more complex. This led to the modified hypothesis that $\rho(T, H)$ could be represented by an equivalent circuit of parallel resistors [10]. Essentially, it is postulated that there

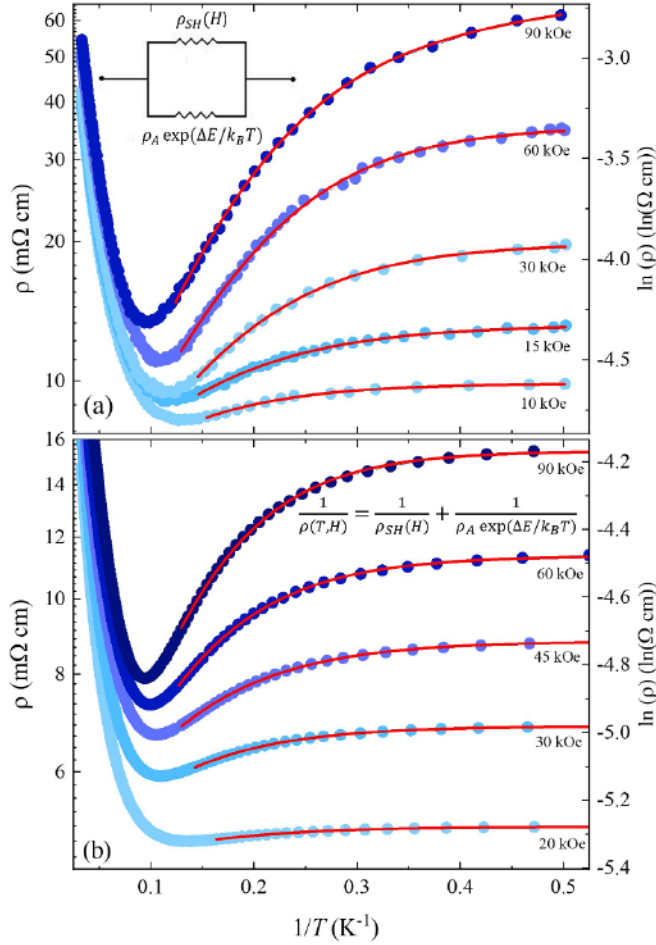


Figure 4. Electrical resistivity (log scale) versus $1/T$. The lines indicate the region of fitting to equation (1).

are three processes for electrical transport in the x - y plane: (1) charge carriers hop between adjacent cyclotron orbits that are in close contact to reach unoccupied Landau energy levels via thermal activation, (2) the charge carriers conduct through the intervening matrix not occupied by cyclotron orbits, and (3) conduction, i.e. physical transport, of the cyclotron-orbits in the x - y plane. The proposed form of the electrical resistivity is

$$\frac{1}{\rho(T, H)} = \frac{1}{\rho_{SH}(H)} + \frac{1}{\rho_A \exp(\Delta E/k_B T)}, \quad (1)$$

where $\rho_A \exp(\Delta E/k_B T)$ is associated with processes (1) and (3) and ρ_{SH} is the temperature-independent shunt resistivity representing process (2).

Results of fitting the data to equation (1) for H above 7.5 kOe and 15 kOe for samples 1 and 2, respectively, are shown in figure 4. The equation represents the data well. ΔE is plotted versus H in figure 5. The linear fit shown in the plot is $\Delta E(H) = E_{FM} + \hbar\omega_c$, where E_{FM} is an activation energy attributed to conduction of the cyclotron orbits (process (3)). One might draw an analogy between cyclotron orbit motion to the motion of flux tubes in a superconductor [27]. In the fitting, the slope

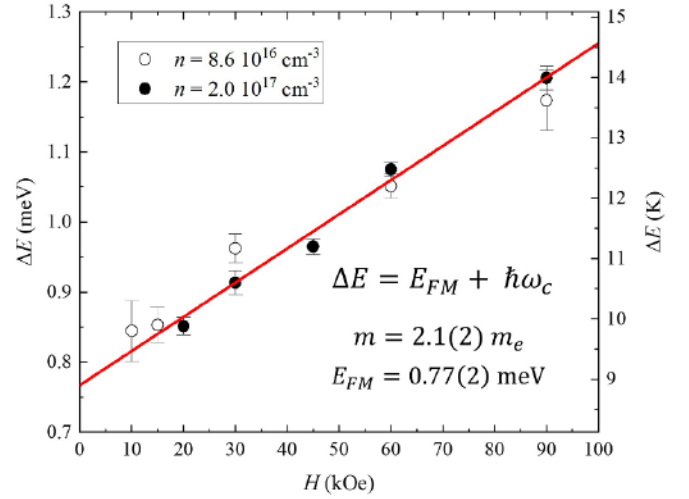


Figure 5. ΔE values obtained from the fits shown in figure 4. The solid line is the linear fit to $\Delta E(H) = E_{FM} + AH$. The slope $A = \hbar e/m$, with $m = 2.1(2)m_e$.

$\hbar e/m$ yields the value $m = 2.1(2)m_e$, which is comparable to the literature value of $1.8m_e$ [7, 26]. $E_{FM} = 0.77(2)$ meV was determined, which is close in magnitude to the other energy scales mentioned here.

The parameters $\rho_{SH}(H)$ and ρ_A , provided in table 1, are briefly addressed. The $\rho_{SH}(H)/\rho_{SH}(0)$ data for both samples collapse onto a single curve, which increases linearly in H . The behavior is likely associated with the reduction in cyclotron orbit area, which will increase charge-carrier scattering. The prefactor ρ_A falls off strongly with magnetic field for both samples. A plot of ρ_A/n reveals that the data for both collapse onto a single curve that is roughly linear in $1/H$, although there is more scatter than observed in the $\rho_{SH}(H)/\rho_{SH}(0)$ data. Since $\mu_B H = \hbar\omega_c/2$ is comparable in magnitude to E_F and $k_B T$, it is feasible that increased magnetic field promotes charge-carrier hopping from doubly-occupied Landau levels to unoccupied levels while also reducing spin-disorder scattering. These would enhance charge mobility. A better understanding of $\rho_{SH}(H)$ and ρ_A would require the study of additional systems other than $\text{SrTiO}_{3-\delta}$, and measurements at more magnetic fields. It is possible that two separate terms to model process (1) process (3) might be sensible. This would add a third fraction to equation (1), leading to more fit parameters. Since the present fitting is adequate, this avenue was not pursued. A detailed theoretical treatment would provide more guidance and a better understanding of fit parameters.

5. Discussion

The influence of Landau levels on the physical properties of solids arises in a number of well-known examples; two are mentioned here. One is the quantum Hall effect, where a limited number of charge carriers are constrained to a thin layer.

Table 1. Parameters obtained from fitting.

$n(\text{cm}^{-3})$	H (kOe)	ρ_{SH} (m Ω cm)	ρ_A (m Ω cm)	ΔE (K)
8.6×10^{16}	10	9.88(2)	10(1)	9.8(5)
	15	13.22(5)	7.5(3)	10.0(3)
	30	19.8(1)	4.1(2)	11.2(2)
	60	35.5(1)	3.5(1)	12.2(2)
	90	75(2)	4.3(2)	13.6(5)
2.0×10^{17}	20	5.10(1)	25.6(6)	9.8(2)
	30	6.88(2)	10.4(1)	10.6(2)
	45	8.82(1)	7.3(1)	11.1(1)
	60	11.34(1)	4.9(1)	12.5(1)
	90	15.46(2)	3.6(1)	14.0(2)

In this case, as magnetic field is increased the electrical conductivity perpendicular to the field drops to zero if the Fermi energy lies between two Landau levels since there are no available states for the charge carriers. Another is the Schubnikov-de Haas effect, which occurs in metals at very low temperatures. Here, as magnetic field increases, the energy of charge carriers in Landau levels near E_F can cross that energy. When this occurs, the charge carriers move to other portions of the Fermi surface with other values of k_z and Landau-level energy [23]. This leads to quantum oscillations in ρ when the thermal layer populated by the charge carriers near E_F is such that $k_B T \ll \hbar\omega_c$, which is generally near or below 1 K.

These two cases exemplify the impact of Landau levels on electrical conduction. They occur at extremely different charge-carrier densities, one very low (and two-dimensional in nature), the other in a typical range of $10^{17} \lesssim n \lesssim 10^{23} \text{ cm}^{-3}$. $\text{SrTiO}_{3-\delta}$ specimens with n values 2 or more times larger than those of the samples of this study exhibit quantum oscillations in $\rho(H)$ [20]. Note that no unusual behavior in the Hall coefficient or mobility is evident in $\text{SrTiO}_{3-\delta}$ at low temperature [30, 31]. The temperatures of the measurements presented here are well above the range where quantum oscillations would be expected, since $k_B T > \hbar\omega_c$ and due to the broadness of the Fermi distribution about E_F . Here it is suggested that Landau levels can lead to a metal–insulator transition. As revealed in figure 2 the specimens are on the verge of a metal–insulator transition, making them very susceptible to charge-carrier localization. Application of magnetic field leads to the formation of cyclotron orbits, whose diameter decreases with increasing magnetic field [11]. Given the doped-semiconductor nature of the $\text{SrTiO}_{3-\delta}$ specimens, at high enough magnetic field the cyclotron orbits can reach a critical diameter comparable to the intercarrier spacing, which leads to charge-carrier localization. The convergence of the energy scales E_F , $\hbar\omega_c$, and $k_B T$ play into the observed behavior. This arises in a few ways. For one, there exist only a small number of discrete Landau levels below E_F . Increasing magnetic field reduces that number, which is likely to enhance charge-carrier localization. Secondly, the very broad energy distribution about E_F (since $E_F \sim k_B T$) increases the probability that charge carriers can reach some Landau levels above E_F .

The empirical model presented here contains three main forms of charge-carrier conduction. The thermally-activated portion in the insulator-like regime is due to hopping to available Landau levels. There is also a contribution due to charge-carrier motion through the matrix intervened by cyclotron orbits. Finally, there is a contribution due to conduction, i.e. physical transport, of the cyclotron orbits in the x - y plane. Fitting the data to this model yields the energy $\hbar\omega_c$ as the energy gap for thermally-activated hopping, providing confidence in the approach. Semiconductors with comparable charge-carrier densities are known to exhibit metal–insulator transitions, which is sometimes referred to as *magnetic freezeout* [11–16, 28, 29]. Thus, our results are not unprecedented, although the model given by equation (1), within which $\hbar\omega_c$ is a key parameter, and the associated fitting shown in figure 4, has not previously been reported, to our knowledge.

Bose-Metal (BM) behavior is briefly addressed here. It emerged from studies of disordered, two-dimensional superconductors, where quantum fluctuations and thermal length scales compete [32] leading to a magnetic-field-induced superconducting to insulator transition (SIT). In the BM scenario, the Cooper pairs localize and the vortex and antivortex pairs Bose condense [33, 34]. The associated dynamical electric field affects the Cooper pairs, leading to their phase incoherence. A scaling argument developed by Das and Doniach [33] to describe $\rho(T, H)$ for the BM is based on dimensional analysis and very general arguments. It is given by the relationship

$$\rho \left[\frac{T^{1/\nu z}}{(H - H_c)} \right]^{\nu(z+2)} = f \left(\frac{H - H_c}{T^{1/z\nu}} \right). \quad (2)$$

The exponents α , ν , and z are interrelated, and to be determined. The value $z = 1$ is associated with the Coulomb interaction [32], and is universally observed.

BM behavior is thought to occur in low-dimensional systems such as thin and patterned films [33, 35–39]. This scaling argument is obeyed for MoGe [36, 40]. It is also unexpectedly obeyed for the quasi-one-dimensional Lithium Purple Bronze [41] and $\text{K}_{0.05}\text{MoO}_{2-\delta}$ [42]. The latter two are cases where superconductivity, or remnants thereof, might not be expected at the magnetic field magnitudes of the studies. Similar scaling has also been reported in bulk samples of graphite and bismuth, where Landau-level quantization was noted [43].

As revealed in figure 6, the $\rho(T, H)$ data for both of our $\text{SrTiO}_{3-\delta}$ specimens obey the scaling of equation (2) remarkably well. No remnants of superconductivity at the temperatures, doping, and magnetic fields of this study are expected for these $\text{SrTiO}_{3-\delta}$ specimens, therefore, it is not proposed that they exhibit BM behavior associated with superconductivity, boson formation, and phase incoherence. The arguments used to obtain equation (2) involve the motion of magnetic vortices and two-dimensional conduction. In the present case, the value $\nu = 4/3$ is observed, which is typical for classical 2D percolation [36]. Rather than vortices and associations to superconductivity, the picture presented here involves charge

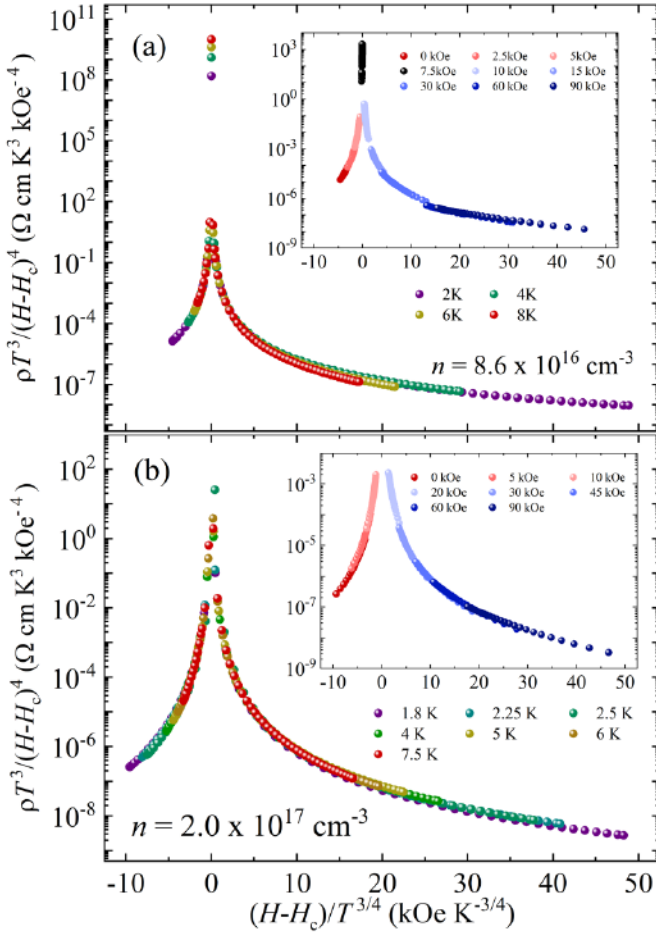


Figure 6. Main panels show the scaling collapse of the $\rho(H)$ curves for each specimen obtained using equation (2) and the data of figure 3. Insets show the scaling collapse of the $\rho(T)$ curves for each specimen obtained using equation (2) and the data of figure 2.

carriers in cyclotron orbits and conduction processes that are largely two-dimensional in nature. Thus, the remarkable scaling collapse revealed in figure 6 for our specimens may simply result from the strong physical analogy between charge carriers in cyclotron orbits and those orbiting magnetic fluxoids, along with the two-dimensional conduction processes present in both systems. Further testing of this scaling and the parallel conduction model presented here for additional systems exhibiting magnetic-field-induced metal–insulator transitions would offer valuable insight into the remarkable scaling collapse revealed here.

6. Conclusions

Magnetic-field-induced metal–insulator transitions were observed in two specimens of $\text{SrTiO}_{3-\delta}$ with charge-carrier densities near 10^{17} cm^{-3} . Magnetic field leads to a new quantization scheme for the charge carriers since they occupy Landau levels. The cyclotron orbit diameter reduces with

increasing magnetic field, eventually shrinking to diameters smaller than the charge-carrier spacing, which promotes their localization. Magnetic field also reduces the number of Landau levels below E_F , further promoting localization. These combined effects are argued to be responsible for the metal–insulator transition. A simple parallel-resistor model was successfully applied suggesting three sources for electrical conduction: (1) conduction due to charge-carrier hopping to unoccupied Landau energy levels via thermal activation with energy gap $\hbar\omega_c$, (2) conduction through the intervening matrix not occupied by cyclotron orbits, and (3) conduction, i.e. physical transport, of the cyclotron orbits. The localization of charge due to the relationship between cyclotron-orbit diameter and charge-carrier spacing discussed here is identical to the concept of *magnetic freezeout* proposed previously for doped semiconductors [11–16, 28, 29]. Our analysis offers more insight into the metal–insulator transition and includes the Landau-level energy explicitly in the model. An unexpected analogy to Bose–Metal behavior was also revealed.

Data availability statement

All data that support the findings of this study are included within the article. They can also be found in the data repository www.scidb.cn/en.

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