1. Introduction

The degree to which the Coulomb interactions among the conduction electrons (‘strong correlations’) drive novel states of matter in real materials and determine their physical properties lies at the center of many unresolved questions in condensed matter physics. Over the past few years, high-quality thin films and heterostructures have emerged as novel platforms to study strong correlation physics. Heterostructures allow for control of parameters that affect the microscopic physics in ways not possible with bulk materials. For example, carrier densities can be introduced without the use of chemical dopants by modulation doping [1, 2] or polar/non-polar interfaces [3, 4] and tuned through field effect [5–7]. Dimensionality can be controlled through electrostatic confinement coupled with layer-by-layer control. Interfaces can be used to induce magnetism [8] or superconductivity [9], to control lattice symmetry [10], orbital, and charge order [11], phonon coupling, or to create artificial materials in superlattice geometries [12]. Coherency strains in epitaxial structures modify lattice parameters and crystal symmetry, with profound influence on phenomena such as metal-insulator transitions. Advanced thin
film growth approaches yield very high quality films [13]. All of these approaches are now being widely applied to complex oxide materials, including those that are strongly correlated, and have led to many interesting new discoveries.

This article focuses on one specific aspect of correlated oxide heterostructures, namely the electric transport properties of itinerant charge carriers. Deviations from conventional metallic behavior are often referred to as ‘non-Fermi liquid’, ‘strange’, or ‘bad metal’ behavior. These terms describe somewhat different phenomena, and we define them in the following sections, but often they appear within the same materials system. They have been studied for many decades in strongly correlated materials, such as the unconventional superconductors and heavy fermion systems [14–19], using measurements of properties, such as the electrical resistance, thermal transport, or conductivity at optical frequencies, as a function of temperature (T), pressure, doping, frequency, or magnetic field. Often, studies were motivated by the idea that the normal (non-supercconducting) state may provide insights into the pairing mechanism that leads to high-temperature superconductivity. Because they remain so profoundly enigmatic, however, in particular when contrasted with the degree of understanding that has been achieved for ‘conventional’ metals and semiconductors, the transport properties of correlated materials are of high scientific interest in their own right.

The level of difficulty is substantial. For example, in strongly correlated materials, non-Fermi liquid behavior is typically considered in the limit of extremely high carrier concentrations, near one electron/unit cell, where carriers are subject to on-site Coulomb interactions and the material is near a ‘Mott’ metal insulator transition. These materials are often in proximity to complex magnetically or electronically ordered states. At the other end of the spectrum lie low-density, 2D electron systems in semiconductors, which show unconventional transport and metal-insulator transitions under the influence of long-range Coulomb interactions [20], with the limiting state being the Wigner crystal. How these two extremes intermesh is a subject of ongoing investigation.

2. Scattering rates that show a $T^2$ temperature dependence

2.1. Longitudinal resistance

The temperature dependence of the electrical resistance of correlated materials typically can be described by power laws. Often a distinction is made between regimes (as a function of some tuning parameter), where the resistance is proportional to $T^2$, which is the behavior expected for a Fermi liquid at low temperatures, and regimes, where it is proportional to $T^n$, where $n$ is a ‘non-Fermi liquid’ exponent with $1 \leq n < 2$. While the $T^2$ Fermi-liquid regime is difficult to detect for conventional metals because it is either overwhelmed by electron-phonon scattering (at high temperatures) or by impurity scattering (at low temperatures) [32], examples of strongly correlated materials that exhibit a pronounced $T^2$ behavior of the resistance, often to high temperatures, abound. To name a few, they include materials as diverse as V$_2$O$_3$ [33], La$_2$–Sr,CuO$_4$ [34], Ag$_2$Pb$_2$O$_6$ [35], NdNiO$_3$ [36], NiS$_2$,Se$_x$ [37], and doped SrTiO$_3$ [38]. In some cases, the quadratic temperature dependence reaches room temperature.

$T^2$ scattering rate is often taken to be a signature of a ‘Fermi liquid’. In a Fermi liquid, electron–electron scattering can give rise to a $T^2$ behavior, because the phase space for scattering is limited to an energy range of $kT$ around the Fermi energy, $E_F$, which is a direct consequence of the Pauli exclusion principle. Specifically, for a Fermi liquid [15]:

$$\frac{1}{\tau_{ee}} \sim \frac{\pi}{\hbar} |V|^2 g_F^2 E^2, \quad (1)$$

where $\tau_{ee}$ is the quasiparticle lifetime, $\hbar$ is the reduced Planck’s constant, $|V|$ is a model-dependent interaction potential, $g_F^2$ is the density of states at the Fermi surface, and $E$ the energy of the quasiparticle. At finite temperatures, $E$ is set by the temperature, so for quasiparticles near the Fermi surface the scattering rate ($1/\tau_{ee}$) is proportional to $T^2$. A momentum relaxation mechanism, such as Umklapp scattering, or a complex Fermi surface, are required for electron–electron scattering to influence the resistivity [39, 40]. Here, we discuss recent studies on thin films that show that taking the $T^2$ behavior to be a signature of a Fermi liquid may not always be correct.

The specific example we discuss here are electron-doped SrTiO$_3$ films. At high temperatures, the mobility of lightly doped SrTiO$_3$ can be described quantitatively by longitudinal optical (LO) phonon scattering of polarons [41–43]. At intermediate temperatures, the resistivity and the Hall mobility show a quadratic temperature dependence (figure 2) [38, 43–45]. The LO phonon scattering is increasingly screened...
as the doping concentration is increased and the $T^2$ behavior can be observed to higher and higher temperatures [43]. The crux of the matter is that SrTiO$_3$ shows a $T^2$ scattering rate at temperatures and electron concentrations where the electron gas is likely non-degenerate [46–49], that is $E_F(T = 0 \text{K}) \ll k_B T$, where $N$ is the 3D carrier density, $h$ is Planck’s constant, and $m^*$ is the effective carrier mass. SrTiO$_3$ shows metallic behavior ($d\rho/dT > 0$) even in the non-degenerate case because the dielectric constant ($\kappa$), and thus the Bohr radius ($a_B$), is large, so that the Mott criterion, $Na_B^2 \sim 0.2$, is fulfilled, where $a_B = h\sqrt{2\alpha/e^2}$. If the Fermi level is low, however, the phase space arguments that lead to a $T^2$ scattering rate in a Fermi liquid according to equation (1) are not applicable. Indeed, in the non-degenerate case the transport is captured by Maxwell-Boltzmann statistics, there is no well-defined Fermi energy and the chemical potential is below the conduction band edge.

If SrTiO$_3$ shows a $T^2$ scattering rate even though it is not a Fermi liquid (it is a classical gas) how about other materials? To discuss this question, consider equation (1), which suggests a strong carrier density dependence of $1/\tau_{ee}$, i.e. via the interaction potential. A simpler, phenomenological equation is often used for the scattering rate of a Fermi liquid [50]:

$$\frac{1}{\tau_{ee}} = B \frac{(k_B T)^2}{\hbar E_F},$$

(2)

where $B$ is a dimensionless factor that incorporates scattering event probabilities. $1/\tau_{ee}$ is expected to depend on the carrier density due to $E_F$ (and $B$). Assuming the resistivity is described by $\rho_{xx} = \rho_0 + A T^2$, where $\rho_0$ is the residual resistivity, then, according to the Drude model:

$$A T^2 = \frac{m^*}{Ne^2} \frac{1}{\tau_{ee}}.$$  

(3)

Measurements of $A$ as a function of carrier density have been reported for several oxides, including cuprates [51–54], vanadates [55], bulk, doped SrTiO$_3$ [56], and SrTiO$_3$ quantum wells [56, 57]. In all cases, $A \sim 1/N$, consistent with expectations from the Drude model, see equation (3). A plot that shows this behavior for doped SrTiO$_3$ appears in figure 3, where $A \sim 1/N$ can be observed over a very large carrier density range in both the non-degenerate and degenerate doping regimes.

The important point is that $A \sim 1/N$ means that the scattering rate, $1/\tau_{ee}$, is independent of the carrier density, contrary to what is expected from Fermi liquid theory, see either equation (1) or equation (2) [56]. Because $A \sim 1/N$ is also observed in materials such as the cuprates which, unlike lightly doped SrTiO$_3$, can be considered strongly correlated materials, this hints strongly at a surprisingly universal $T^2$ scattering rate that is not due to electron–electron scattering in a Fermi liquid.
Key Issues Review

2.2. Hall mobility or Hall angle

Strongly correlated materials often show resistances that depart from the quadratic dependence on temperature (we will discuss these in the next section). In contrast, the Hall angle (\(\cot \theta\)), which is the inverse of the Hall mobility, almost always shows a very robust \(T^2\) temperature dependence [34, 53, 58–61]. This observation has become known as ‘two lifetime’ behavior, because it suggests that different scattering rates control the Hall mobility and the longitudinal resistance, respectively [62]. In addition to the cuprates, lifetime separation has been observed in a wide range of correlated materials, including \(V_2O_3\) [63], ruthenates [64, 65], heavy Fermion systems [66, 67], \(MgB_2\) [68], and in oxide heterostructures [57]. Figure 4 shows an example of the two lifetime phenomenon for a high-carrier-density, quasi-two-dimensional electron system at a \(SmTiO_3/SmTiO_3\) interface that is close to a metal-insulator transition. Unlike the lightly doped \(SrTiO_3\) films discussed in the previous section, this electron system is degenerate. The resistance is \(\sim T^{5/3}\) above \(\sim 100\) K, while the Hall angle is always \(\sim T^2\) [69].

Lifetime separation was also investigated in quantum wells of \(SrTiO_3\) [57, 70], such as formed in \(SmTiO_3/SmTiO_3\) heterostructures, which contain mobile charge densities on order of \(7 \times 10^{14} \text{ cm}^{-2}\) and which exhibit numerous correlated phenomena, such as itinerant magnetism and pseudogaps, when their thicknesses are reduced to a few atomic planes. These studies showed that the lifetime separation can have two components, namely the different temperature dependencies of Hall angle and longitudinal resistances, as seen in figure 4, but also a divergence in their 0-K residuals [57]. Both lead to a temperature dependence of the Hall coefficient even when there is no major change in the Fermi surface or carrier density. These two contributions to the lifetime separation may have different origins. In the \(SrTiO_3\) quantum wells, the divergence of the 0-K scattering rates appeared only near a quantum critical point close to a transition to an itinerant magnetic phase [57]. Further analysis of the 0-K residuals suggested that the proximity to the quantum critical point influenced the residual in the Hall angle, but not that of the

Figure 2: Temperature dependence of the resistivity and Hall mobility of La-doped \(SrTiO_3\) films (data from [126]). (a) Log–log plot of the temperature derivative of the resistivity, \(\partial \rho / \partial T\), versus temperature, for films with different carrier concentrations. A power law behavior gives a straight line in such a plot. In an intermediate temperature range, the resistivity behaves as \(T^2\), as indicated by the black dashed lines. (b) Hall mobility as a function of temperature for the film with a carrier density of \(2 \times 10^{18} \text{ cm}^{-3}\) (symbols). As discussed in [43], the mobility can be described completely by just three terms: a temperature-independent impurity scattering term, \(\mu_0\), which dominates at low temperatures, a LO phonon-polaron scattering term, \(\mu_{LO}\), which dominates at high temperatures, and a term that is proportional to \(T^{-2}\). More details about the LO phonon term can be found in [41]. The results for the fit parameters can be found in [43]. The different lines indicate the contribution of each term and their sum describes the experimental data extremely well, see solid red line. For similar fits for films with different carrier densities, see the supplementary information to [43].

Figure 3: Carrier density dependence of the A-coefficient of the \(T^2\) resistivity term for 3D electron gases in \(SrTiO_3\) doped with different dopants (see legend). Data is from thin films (La:SrTiO3 and Gd:SrTiO3) grown by MBE and bulk single crystal data from [44, 45]. The A-coefficient approximately follows a \(1/N\) dependence on the carrier density \(N\) over orders of magnitude in \(N\), as can be seen by comparison with the black dotted line. Slight deviations from the \(1/N\) behavior are expected even if the scattering rate is independent of the carrier density, because the carrier mass also changes as higher lying bands are filled. Reprinted from [56]. CC BY 4.0.
Temperature dependence of the sheet resistance (a) and Hall angle (b) of a quasi-two-dimensional electron liquid at the SmTiO$_3$/SrTiO$_3$ interface, which has a sheet carrier density of $\sim 2 \times 10^{14}$ cm$^{-2}$, due to the polar discontinuity at the interface. The Hall angle, cot$\theta$, is the inverse of the Hall mobility, $\mu_H$. $\text{Hcot}\theta = \mu_H$, where $H$ is the magnetic field. The sheet resistance follows a $T^{5/3}$ temperature dependence at elevated temperatures, then shows a dip, followed by a small temperature interval of $\sim T^2$, due to the polar discontinuity at the interface. In contrast to the complicated behavior of the resistance, the Hall angle follows a $T^2$ temperature dependence almost over the entire temperature range. Note that the LO phonon scattering term at high temperatures, which is clearly seen for the low density, 3D electron gas in figure 1(b), is absent here, due to the screening of the LO phonons at the high electron density. Data is from [69].

Figure 4. Temperature dependence of the sheet resistance (a) and Hall angle (b) of a quasi-two-dimensional electron liquid at the SmTiO$_3$/SrTiO$_3$ interface, which has a sheet carrier density of $\sim 2 \times 10^{14}$ cm$^{-2}$, due to the polar discontinuity at the interface. The Hall angle, cot$\theta$, is the inverse of the Hall mobility, $\mu_H$. $\text{Hcot}\theta = \mu_H$, where $H$ is the magnetic field. The sheet resistance follows a $T^{5/3}$ temperature dependence at elevated temperatures, then shows a dip, followed by a small temperature interval of $\sim T^2$, due to the polar discontinuity at the interface. In contrast to the complicated behavior of the resistance, the Hall angle follows a $T^2$ temperature dependence almost over the entire temperature range. Note that the LO phonon scattering term at high temperatures, which is clearly seen for the low density, 3D electron gas in figure 1(b), is absent here, due to the screening of the LO phonons at the high electron density. Data is from [69].

longitudinal resistance. In the cuprates, the 0-K divergence in scattering rates has been explained with anisotropies in the elastic scattering rates [71]. In a recent study of SmTiO$_3$/SrTiO$_3$/SmTiO$_3$ quantum wells, we showed that disorder affected the residuals in both the Hall angle and longitudinal resistances, but it did not affect their 0-K divergence [70].

There currently exists no generally accepted understanding of lifetime separation [72]. Suggested explanations include a 2D Luttinger liquid (spin-charge separation), complex Fermi surfaces combined with strongly anisotropic scattering rates, as may occur near an antiferromagnetic transition, bipolarons, and quantum critical points [18, 54, 62, 73–78]. Most theoretical models aimed at reproducing $R \sim T$ and cot$\theta \sim T^2$, which, unfortunately, does not apply to all of the materials for which lifetime separation is observed, such as the SrTiO$_3$ interfacial electron systems. One point of view is to take the $T^2$ Hall scattering rate as a signature of an underlying Fermi liquid state even though the resistance departs from simple behavior [53]. In the light of what was discussed above, namely that a $T^2$ scattering rate may not always indicate a Fermi liquid, this interpretation should be taken with some degree of caution.

To summarize section 2, there are a surprising number of common features in the transport of a wide range of correlated materials and complex oxide heterostructures: a Hall angle (inverse of the Hall mobility) that remains robustly $T^2$, independent of the specific temperature dependence of the longitudinal resistance, and a scattering rate that does not appear to be overly sensitive to factors such as the carrier density, electronic structure, or even whether the electron system is degenerate or non-degenerate. Coupling to the lattice should certainly be considered in any future developments of an understanding of the unusual transport properties of oxides, as will also be discussed in the following sections. The quasiparticle mass in SrTiO$_3$ at low temperatures is enhanced by a factor of two, most likely due to dressing by phonons [79], as is also seen in angle resolved photoemission [80]. Similar to electron–electron scattering in metals [32], the pronounced $T^2$ scattering rate, which often extends to very high temperatures, appears to be a feature for electrons in conduction bands derived from d-states. For example, a degenerate perovskite oxide system with an s-band conduction band, La-doped BaSnO$_3$, does not exhibit a $T^2$ scattering rate in its resistance [81]. The findings illustrate the need for a theoretical framework that can explain (i) the universal $T^2$ scattering rate and, equally important, (ii) its peculiar robustness in the Hall angle. By universal we mean that it encompasses high-carrier-density, correlated materials as well as low-density systems such as SrTiO$_3$.

### 3. $T^n$ power laws in the electrical resistivity

Departures from $T^2$ behavior in the longitudinal resistance to other power laws of form $T^n$, with $1 \leq n \leq 2$, are ubiquitous. These power laws are often identified as signatures of non-Fermi liquids. The extreme case are the superconducting cuprates, which show $T$-linear behavior in the normal state, sometime referred to as ‘strange metal’ behavior.

One possible explanation for non-Fermi liquid behavior are quantum critical points [15]. Near a magnetic or other instability, the associated order parameter fluctuations may lead to strong scattering and non-Fermi-liquid behavior [82]. Oxide heterostructures allow for testing these ideas by using tuning parameters, such as epitaxial strain, to bring a material system close to a quantum critical point. Here, we discuss results from epitaxial NdNiO$_3$ films.

Metallic rare earth nickelates (except LaNiO$_3$) possess an orthorhombic perovskite-derived crystal structure (space group $Pbnm$). They exhibit temperature-driven metal-insulator transitions, whose transition temperature depends on the size of the rare earth ion and degree of oxygen octahedral tilts in the orthorhombic structure, which control the bandwidth [31].
The symmetry of the insulating, low-temperature, antiferromagnetic phase is monoclinic (P$\overline{2}$1) [83, 84]. In this space group, the presence of two inequivalent Ni sites allow for 1:1 charge order [85] (or ‘bond-length disproportionation’, since the actual charge on the two Ni sites may not be very different [86, 87]). The electrical resistivity of the rare earth nickelates above the metal-insulator transition exhibits $T^\nu$ behavior and various exponents of $n \sim 4/3$, 5/3, or 2 have been reported [36, 88–90]. The rare earth nickelates are therefore an interesting system to investigate various power laws in transport in proximity to metal-insulator transitions.

As shown in [36], the temperature dependence of the resistivity of the rare earth nickelates in the metallic phase can be described by the following equation:

$$\frac{1}{\rho} = \frac{1}{\rho_{\text{ideal}}} + \frac{1}{\rho_{\text{sat}}} \quad (4)$$

where $\rho_{\text{sat}}$ is a saturation resistivity. As will be discussed in the next section, resistivity saturation is important in modeling transport when the scattering rate is high and $\rho_{\text{ideal}}$ becomes large. Although there are materials that do not show saturation, neglecting $\rho_{\text{sat}}$ [89, 91] in case of the nickelates yields incorrect values for $n$ [36]. In many correlated materials, $\rho_{\text{ideal}}$ is described by a power law:

$$\rho_{\text{ideal}} = \rho_0 + A T^n. \quad (5)$$

Figure 5 shows results for epitaxial NdNiO$_3$ films, which were coherently strained to substrates having different signs and degrees of lattice mismatch [36]. It was shown that $n$ assumes just two values, either $n = 2$ or $n = 5/3$ [36]. Specifically, if the metal-insulator transition was suppressed, which is the case for in-plane compressive strains, then $n = 5/3$. Electron diffraction studies showed that films under compressive strains adopt space group P$\overline{2}$1$_m$ [92], which is expected from symmetry arguments discussed in [93]. The P$\overline{2}$1$_m$ space group does not allow for 1:1 charge order, which would require further lowering of the symmetry [92], which is not possible in films that are coherently constrained to a substrate. In contrast, films under tensile strain possess orthorhombic symmetry, which allows for the transition to the charge ordered, insulating state [92].

Thus, thin film studies establish the following about this strongly correlated system: (i) the metal-insulator transition in the rare earth nickelates is suppressed if the heterostructure boundary conditions prevent establishment of a 1:1 charge order. In other words, 1:1 charge order is a requirement for the insulating state. (ii) The non-Fermi liquid exponent of $n = 5/3$ is associated with the suppression of the 1:1 charge ordered insulating state. On first sight, (ii) appears consistent with theories that ascribe non-Fermi liquid exponents to order parameter fluctuations; in this case it may be associated with the suppression of charge and antiferromagnetic order, and a nearby quantum critical point. Interestingly, both types of metals (both symmetries) exhibit pseudogaps (a depletion of the single particle density of states), which, in the case when the insulator is not suppressed, develops into a full gap [94]. Pseudogaps are typically associated with incipient antiferromagnetic order. We note, however, that there are just two exponents observed in the entire phase diagram in figure 4. This observation points to a picture of specific, fractional exponents in the temperature dependence of the resistivity that are firmly tied to a specific non-Fermi liquid phase, with a distinct symmetry. A similar case of a ‘non-Fermi liquid phase’ has been made previously for the itinerant ferromagnet MnSi [95].

4. Mott–Ioffe–Regel-limit and resistance saturation

At high temperatures, two types of behaviors of the electrical resistance of high-resistance materials can be distinguished: (i) the resistance increases seemingly without limit or (ii) it ‘saturates’ by slowly approaching a finite value. The
non-saturating behavior (i) has become known as ‘bad metal behavior’ [96]. It has attracted attention because unconventional superconductors in their normal state are non-saturating and it is considered a signature of a novel kind of metallic state [96]. Neither case is, however, fully understood [97–104]. Confusion arises from the fact that the Mott–Ioffe–Regel limit appears in the discussion, so we discuss this briefly first.

4.1. Mott–Ioffe–Regel limit

The resistances of thin metal oxide films are often sufficiently high that they reach or exceed the Mott–Ioffe–Regel limit. This limit is the resistance when the scattering of the carriers becomes so strong that \( l k_F \sim 1 \), where \( l \) is the mean free path of the carriers and \( k_F \) the Fermi wave vector [105, 106]. An approximate value for the Mott–Ioffe–Regel limit in two dimensions is \( \hbar e^2 / l \) [107]. It is well-established that is relevant in the regime of elastic scattering \( \text{at low temperatures} \), i.e. it establishes a criterion where a planar wave description no longer makes any sense [26, 104]. A 2D electron system that, for any reason, exceeds a sheet resistance on order of \( \hbar e^2 / l \) at low temperatures may thus be expected to be localized. In three dimensions, there is an additional factor \( k_F^{-1} \) [107]. In keeping with this expected behavior, there are ubiquitous observations of oxide thin films and heterostructures that exhibit insulating behavior at all temperatures at low film thicknesses, because their resistance exceeds the Mott–Ioffe–Regel limit [108–111]. Figure 6 shows an example of this behavior for a LaNiO3 film [112]. The point here is that the observation of insulating behavior in such cases should not be used as evidence of a correlation-induced metal-insulator transition. Often, the resistivity also increases as the film thickness is reduced. This can be due to a number of reasons, such as increased scattering from surfaces and interfaces. Another reason is bandwidth narrowing, which is related to the octahedral tilts in the distorted perovskite structure that these oxides adopt. Connectivity with the substrate and film strain all affect the octahedral tilts [10, 113]. For example, thin LaNiO3 films exhibit octahedral tilt patterns near the interface with a substrate that are different from those in the bulk and which cause a high resistivity, and insulating behavior below a critical thickness as the Mott–Ioffe–Regel limit is exceeded. In contrast, LaNiO3 films of the same thickness embedded in superlattices remain metallic, which can be explained with their different octahedral tilt patterns [113]. Films further in the metallic regime typically show weak localization behavior [114] at low temperatures, which is manifested as an upturn in the resistance at low temperatures, also seen in figure 6.

One unfortunate consequence of the high resistances in thin films due to the inherently low carrier mobilities of correlated materials, and associated localization when the Mott–Ioffe–Regel limit is exceeded, is that it makes it difficult to study correlation effects in \textit{itinerant}, low-dimensional systems, which are pre-empted by this ‘trivial’ localization. An example of interesting phenomena that may emerge when resistances are kept well below the Mott–Ioffe–Regel limit is a novel metal-insulator transition in an interfacial electron system at the SmTiO3/SrTiO3 interface [69].

4.2. High temperatures: saturating and non-saturating metals

Returning to the high temperature characteristics, we remark that at high temperatures the scattering is largely inelastic. Multiple scattering and phase coherence, features of transport at the low temperature localization transition are not important at high temperature. Saturating metals are well described by the parallel resistor formula, equation (4). This formula emerges in a transport model that invokes the Mott–Ioffe–Regel limit as a cut-off time, \( \tau_0 \), for the mean time between electron scattering, \( \tau > \tau_0 = a / v_F \) [115]. The physical basis of this model is that it suggests there should be no transport time scale shorter than the time it takes an electron to move across a unit cell. Following [115], Hussey et al use this approach with some modifications to obtain the parallel resistor model as well as an intuitive frequency dependent conductivity that consists of a Drude response that is broadened and disappears at high temperature leaving a broad incoherent tail that extrapolates to \( \rho_{\text{sat}} \) at low frequency [104]. Time scales, high frequency dynamics, and incoherent high frequency tails are discussed in [102]. While \( \rho_{\text{sat}} \) invokes the Mott–Ioffe–Regel criterion, its precise value for any given system is determined by important details. Since \( \rho_{\text{sat}} \) is an important feature...
in complex materials, estimates of the expected value of the maximum scattering rate and the other material parameters that determine the saturated conductivity need to be taken with a grain of salt and can differ from reasonable estimates by orders of magnitude.

It is important to appreciate that the effect of scattering rate saturation and $\rho_{\text{sat}}$ will emerge in the experimental measurement well below resistivity saturation and must be included in fits to experimental data to extract $\rho_{\text{ideal}}$, as was emphasized in section 3. The degree to which it affects the data depends on the relative values of $\rho_{\text{sat}}$, $\rho_0$, and $A$. Figure 7 shows these values for the NdNiO$_3$ films discussed in section 3 [36]. $\rho_{\text{sat}}$ increases with increasing epitaxial coherency strain. Strains lift the orbital degeneracy of the Ni $e_g$ states [116, 117], and the magnitude of $\rho_{\text{sat}}$ is sensitive to these changes in the electronic structure. Furthermore, while $\rho_0$ increases sharply with decreasing film thickness, $\rho_{\text{sat}}$ is insensitive to it. This results in a critical film thickness for each mismatch strain at which the condition $\rho_{\text{sat}} \sim \rho_0$ is fulfilled, and these films are insulating. This can be understood from equation (4): if $\rho_{\text{sat}} \sim \rho_0$, then the first term becomes small at finite temperatures compared to $1/\rho_{\text{sat}}$, which represents the incoherent (non-Drude) part, and such a film cannot be a metal anymore.

We finally note that while much theoretical effort has been expended to understand the absence of resistance saturation in some degenerate electron liquids [97–100, 104], so called ‘bad metals’, the absence of resistance saturation at high temperatures in low-density SrTiO$_3$, is probably neither ‘strange’ or ‘bad’, contrary to [118]. The system is a non-degenerate electron gas and as such is described by Maxwell-Boltzmann statistics. Assuming a mean free path no shorter than a unit cell dimension, $\sim \alpha$, the shortest effective scattering time, $\tau$, may be related to the thermal velocity, $v_{\text{th}}$, as $\tau = a/v_{\text{th}}$. The thermal velocity, $v_{\text{th}} = (2k_B T/m^*)^{1/2}$ increases as $T^{1/2}$ and one can estimate the temperature dependent upper bound to the high temperature resistivity by $\rho_{\text{sat}} \approx (m^*/ne^2)[v_{\text{th}}/a]$. We expect no saturation of the high temperature resistivity for this non-degenerate system; $\rho_{\text{sat}}$ would increase with temperature. Furthermore, transport in SrTiO$_3$ at high temperatures is described by large polarons and one expects a strong increase in effective mass [119–121]. The experimental data shows that the resistivity rises substantially faster than that given by the temperature dependence of $v_{\text{th}}$ alone, indicating an increase in $m^*$. Taking a mass of $\sim 5m^*$ at room temperature, we estimate a room temperature resistivity bound of $\sim 5 \, \Omega \, \text{cm}$ at an electron concentration of $\sim 4 \times 10^{17} \, \text{cm}^{-3}$. The data in [118] does not violate this bound. Alternatively, one can take the room temperature resistivity of $\sim 4 \times 10^{17} \, \text{cm}^{-3}$, and a thermal velocity based on a mass of $\sim 5m^*$ and extract a mean free path of roughly $\sim \alpha$. If we accept these assumptions, low-doped SrTiO$_3$ is a well-behaved semiconductor at room temperature and not a bad or strange metal.

We also note that Boltzmann theory applies for phonon scattering in metals at most temperatures [122], even though the room temperature scattering rate is very large, $\sim k_B T/h$ [123–125]. Indeed, the high temperature mobility of doped SrTiO$_3$ can be quantitatively described by a gas of polarons that scatters on LO phonons [42, 43], even though it has a very large scattering rate.

5. Conclusions

In summary, anchoring our discussion with transport in doped SrTiO$_3$, which appears to be a well-behaved electron gas or liquid albeit with a poorly understood $T^2$ scattering rate, other oxide heterostructures and thin films exhibit many non-Fermi liquid phenomena, such as power laws in the temperature dependence of the resistance, lifetime separation, and resistance saturation. Because of the additional degrees of freedom, thin film studies...
allow for illuminating key questions, such as the role of coupling to the lattice in the transport behavior. While some phenomena, such as localization as resistances exceed the Mott–Ioffe–Regel limit, can be understood based in classical models, many others cannot be captured even qualitatively within the framework of the existing descriptions of transport. These include the robust and surprising universal dependence of the Hall angle and fractionalized non-Fermi liquid exponents that signify new phases. It is obvious that a new description of charge carrier transport and interactions is likely needed that applies and generalizes to a much wider class of materials than those traditionally considered in the existing models of non-Fermi liquid behavior.

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References

[1] Son J, Jalan B, Kajdos A P, Balents L, Allen S J and Stemmer S 2011 Probing the metal–insulator transition of NdNiO3 by electrostatic doping Appl. Phys. Lett. 99 192107
[2] Kajdos A P, Ouellete D G, Cain T A and Stemmer S 2013 Two-dimensional electron gas in a modulation-doped SrTiO3/SrTi,ZrO3 heterostructure Appl. Phys. Lett. 103 082120
[3] Ohtomo A and Hwang H Y 2004 A high-mobility electron gas at the LaAlO3/SrTiO3 heterointerface Nature 427 423–6
[4] Stemmer S and Allen S J 2014 Two-dimensional electron gases at complex oxide interfaces Annu. Rev. Mater. Res. 44 151–71
[5] Ahn C H et al 2006 Electrostatic modification of novel materials Rev. Mod. Phys. 78 1185–212
[6] Ahn C H, Gariglio S, Paruch P, Tybell T, Antognazza L and Triscone J M 1999 Electrostatic modulation of superconductivity in ultrathin GdBa2Cu3Oyfilms Science 284 1152–5
[7] Newns D M, Misewich J A, Tsuei C C, Gupta A, Scott B A and Schrott A 1998 Mott transition field effect transistor Appl. Phys. Lett. 73 780–2
[8] Hellman F et al 2017 Interface-induced phenomena in magnetism Rev. Mod. Phys. 89 025006
[9] Gozar A, Logvenov G, Kourkoutis L F, Bollinger A T, Giannuzzi L A, Muller D A and Bozovic I 2008 High-temperature interface superconductivity between metallic and insulating copper oxides Nature 455 782–5
[10] Rondinelli J M, May S J and Freeland J W 2012 Control of octahedral connectivity in perovskite oxide heterostructures: an emerging route to multifunctional materials discovery MRS Bull. 37 261–70
[11] Frano A et al 2016 Long-range charge-density-wave proximity effect at cuprate/manganite interfaces Nat. Mater. 15 831–4
[12] May S J, Santos T S and Bhattacharyya A 2009 Onset of metallic behavior in strained (LaNiO3)x(SrMnO3)1−x superlattices Phys. Rev. B 79 115127
[13] Schlov D G 2015 Perspective: Oxide molecular-beam epitaxy rocks! APL Mater. 3 062403
[14] Sachdev S 2014 Quantum Phase Transitions 2nd edn (Cambridge: Cambridge University Press)
[15] Schofield A J 1999 Non-Fermi liquids Contemp. Phys. 40 95–115
[16] Varma C M, Nussinov Z and van Saarloos W 2002 Singular or non-Fermi liquids Phys. Rep. 361 267–417
[17] Metzner W, Castellani C and Castro C D 1998 Fermi systems with strong forward scattering Adv. Phys. 47 317–445
[18] Anderson P W 1995 New physics of metals: Fermi surfaces without Fermi liquids Proc. Natl. Acad. Sci. 92 6668–74
[19] Stewart G R 2001 Non-Fermi-liquid behavior in d- and f-electron metals Rev. Mod. Phys. 73 797–855
[20] Spiwak B, Kravchenko S V, Kivelson S A and Gao X P A 2010 Colloquium: Transport in strongly correlated two dimensional electron fluids Rev. Mod. Phys. 82 1743–66
[21] Emin D 2013 Polarons (Cambridge: Cambridge University Press)
[22] Miranda E and Dobrosavljevic V 2005 Disorder-driven non-Fermi liquid behaviour of correlated electrons Rep. Prog. Phys. 68 2373–408
[23] Belitz D and Kirkpatrick T R 1994 The Anderson–Mott transition Rev. Mod. Phys. 66 261–390
[24] Chakhalian J, Freeland J W, Millis A J, Panagopoulos C and Rondinelli J M 2014 Colloquium: emergent properties in plane view: strong correlations at oxide interfaces Rev. Mod. Phys. 86 1189–202
[25] Kravchenko S V and Sarachik M P 2004 Metal–insulator transition in two-dimensional electron systems Rep. Prog. Phys. 67 1–44
[26] Lee P A and Ramakrishnan T V 1985 Disordered electronic systems Rev. Mod. Phys. 57 287–337
[27] Moetakef P, Jackson C A, Hwang J, Balents L, Allen S J and Stemmer S 2012 Toward an artificial Mott insulator: correlations in confined high-density electron liquids in SrTiO3 Phys. Rev. B 86 201102
[28] Jackson C A and Stemmer S 2013 Interface-induced magnetism in perovskite quantum wells Phys. Rev. B 88 180403
[29] Marshall P B, Mikheev E, Raghavan S and Stemmer S 2016 Pseudogaps and emergence of coherence in two-dimensional electron liquids in SrTiO3 Phys. Rev. Lett. 117 046402
[30] Need R F, Isaac B J, Kirby B J, Borchers J A, Stemmer S and Wilson S D 2016 Interface-driven ferromagnetism within the quantum wells of a rare earth titanate superlattice Phys. Rev. Lett. 117 037205
[31] Torrance J B, Lacorre P, Nazzal A I, Ansalado E J and Niedermayer C 1992 Systematic study of insulator-metal transitions in perovskites RNiO3 (R = Pr,Nd,Sm,Eu) due to closing of charge-transfer gap Phys. Rev. B 45 8209–12
[32] Kaveh M and Wiser N 1984 Electron-electron scattering in conducting materials Adv. Phys. 33 257–372
[33] McWhan D B and Rice T M 1969 Critical pressure for the metal–semiconductor transition in V2O3 Phys. Rev. Lett. 22 887–90
[34] Ando Y, Kurita Y, Komiya S, Ono S and Segawa K 2004 Evolution of the Hall coefficient and the Peculiar electronic structure of the cuprate superconductors Phys. Rev. Lett. 92 197001

[35] Yonezawa S and Maeno Y 2004 Nonlinear temperature dependence of resistivity in single Ag$_x$Pb$_{1-x}$O$_7$ Phys. Rev. B 70 184523

[36] Mikheev E, Hauser A J, Himmetoglu B, Moreno N E, Janotti A, Van de Walle C G and Stemmer S 2015 Tuning bad metal and non-Fermi liquid behavior in a Mott material: rare earth nickelate thin films Sci. Adv. 1 e1500797

[37] Honig J M and Spalek J 1998 Electronic properties of NiS$_2$. Se$_2$ single crystals: from magnetic Mott–Hubbard insulators to normal metals Chem. Mater. 10 2910–29

[38] Baratoff A and Binnig G 1981 Mechanism of superconductivity in SrTiO$_3$ Physica B 108 1335–6

[39] Pal H K, Yadson V I and Maslov D L 2012 Resistivity of non-Gallium-invariant Fermi- and non-Fermi liquids Likh. J. Phys. 52 142–64

[40] Gurzhi R N 1965 Some features of the electrical conductivity of metals at low temperatures Sov. Phys. JETP 20 93–60

[41] Frederikse H P R and Hosler W R 1967 Hall mobility in SrTiO$_3$ Phys. Rev. Lett. 16 822–7

[42] Verma A, Kajdos A P, Cain T A, Stojkovic B P and Pines D 1997 Theory of the longitudinal resistivity in n-type SrTiO$_3$ Phys. Rev. Lett. 79 205111

[43] Mikheev E, Himmetoglu B, Kajdos A P, Moetakef P, Cain T A, Van de Walle C G and Stemmer S 2015 Limitations to the room temperature mobility of two- and three-dimensional electron liquids in SrTiO$_3$ Appl. Phys. Lett. 106 062102

[44] van der Marel D, van Mechelen J L M and Mazin I I 2011 Common Fermi-liquid origin of T$_c$ resistivity and superconductivity in n-type SrTiO$_3$ Phys. Rev. B 84 233104

[45] Lin X, Faqueb B and Belmia K 2015 Scalable T$_c$ resistivity in a small single-component Fermi surface Science 349 945–8

[46] Shirai K and Yamanaka K 2013 Mechanism behind the high thermoelectric power factor of SrTiO$_3$ by calculating the transport coefficients J. Appl. Phys. 113 053705

[47] Jalan B and Stember S 2010 Large Seebeck coefficients and thermoelectric power factor of La-doped SrTiO$_3$ thin films Appl. Phys. Lett. 97 042106

[48] Swift M W and Van de Walle C G 2017 Conditions for T$_c$ resistivity from electron–electron scattering Eur. Phys. J. B 90 151

[49] Maslov D L and Chubukov A V 2017 Optical response of correlated electron systems Rep. Prog. Phys. 80 026503

[50] Ashcroft N W and Mermin N D 1976 Solid State Physics (Belmont: Brooks/Cole)

[51] Hussey N E, Gordon-Moys H, Kokalj I and McKenzie R H 2013 Generic strange-metal behaviour of overdoped cuprates J. Phys.: Conf. Ser. 449 012004

[52] Barisci N, Chan M K, Li Y, Yu G, Zhao X, Dressel M, Smontara A and Greven M 2013 Universal sheet resistance and revised phase diagram of the cuprate high-temperature superconductors Proc. Natl Acad. Sci. 110 12235–40

[53] Li Y, Tabis W, Yu G, Barisci N and Greven M 2016 Hidden Fermi-liquid charge transport in the antiferromagnetic phase of the electron-doped cuprate superconductors Phys. Rev. Lett. 117 197001

[54] Lee D K K and Lee P A 1997 Transport phenomenology of a holon–spinon fluid J. Phys.: Condens. Matter 9 10421–8

[55] Oka D, Hirose Y, Nakao S, Fukumura T and Hasegawa T 2015 Intrinsic high electrical conductivity of stoichiometric SrNbO$_3$ epitaxial thin films Phys. Rev. B 92 205102

[56] Mikheev E, Raghavan S, Zhang J Y, Marshall P B, Kajdos A P, Balew L and Stemmer S 2016 Carrier density independent scattering rate in SrTiO$_3$-based electron liquids Sci. Rep. 6 20865

[57] Mikheev E, Freeze C R, Isaac B J, Cain T A and Stemmer S 2015 Separation of transport lifetimes in SrTiO$_3$-based two-dimensional electron liquids Phys. Rev. B 91 165125

[58] Chien T R, Wang Z Z and Ong N P 1991 Effect of Zn impurities on the normal-state Hall angle in single-crystal YBa$_2$Cu$_3$O$_y$ Phys. Rev. Lett. 67 2088–91

[59] Carrington A, Mackenzie A P, Lin C T and Cooper J R 1992 Temperature-dependence of the Hall angle in single-crystal YBa$_2$Cu$_3$O$_y$ Phys. Rev. Lett. 69 2855–8

[60] Ogino M, Watanabe T, Tokiwa H, Iyo A and Ishara H 1996 Hall effect of superconducting copper oxide, Cu–1234 Physica C 258 384–8

[61] Xiao G, Xiong P and Cieplak M Z 1992 Universal Hall effect and resistivity of high-Fe,Co,Ni,Zn,Ga Phys. Rev. B 46 8687

[62] Anderson P W 1991 Hall-effect in the 2-dimensional Luttinger liquid Phys. Rev. Lett. 67 2092–4

[63] Rosenbaum T F, Husmann A, Carter S A and Honig J M 1998 Temperature dependence of the Hall angle in a correlated three-dimensional metal Phys. Rev. B 57 R13997–9

[64] Laad M S, Bradaric I and Kusmartsev F V 2008 Orbital non-Fermi-liquid behavior in cubic ruthenates Phys. Rev. Lett. 100 096402

[65] Ting Y A, Liu Y, He T and Cava R J 2011 Magnetotransport properties of BaRuO$_3$: observation of two scattering rates Phys. Rev. B 84 233104

[66] Nair S, Wright S, Friedemann S, Steglich F, Si Q and Schofield A J 2012 Hall effect in heavy fermion metals Adv. Phys. 61 583–664

[67] Nakajima Y, Iwasa K, Matsuda Y, Uji S, Terashima T, Shishido H, Settai R, Ondu Y and Kontani H 2004 Normal-state Hall angle and magnetoresistance in quasi-2D heavy fermion CeCoIn$_5$ near a quantum critical point J. Phys. Soc. Japan. 73 5–8

[68] Gao W N, Kim H-J, Choi E-M, Kim H J, Kim K H P, Lee H S and Lee S-I 2002 Hall effect in c-axis-oriented MgB$_2$ thin films Phys. Rev. B 65 134508

[69] Ahadi K and Stemmer S 2017 Novel metal–insulator transition at the SmTiO$_3$/SrTiO$_3$ interface Phys. Rev. Lett. 118 236803

[70] Marshall P B, Kim H and Stemmer S 2017 Disorder versus two transport lifetimes in a strongly correlated electron liquid Sci. Rep. 7 10312

[71] Narduzzo A, Albert G, French M M J, Mangkorntong N, Zheleznyak A T, Yakovenko V M, Drew H D and Mazin I I 2008 Violation of the isotropic mean free path approximation for overdoped La$_{1.86}$Sr$_{0.14}$CuO$_4$ systems (A = Fe,Co,Ni,Zn,Ga) Phys. Rev. Lett. 107 236803

[72]али Timofeev A, Belkov A and Pines D 1996 How should we interpret the two transport relaxation times in the cuprates? J. Phys.: Condens. Matter 8 9985–10015

[73] Zheleznyak A T, Yakovenko V M, Drew H D and Mazin I I 2008 Phenomenological interpretations of the ac Hall effect in the normal state of YBa$_2$Cu$_3$O$_7$ Phys. Rev. B 75 3089–98

[74] Ong N P 1991 Geometric interpretation of the weak-field Hall conductivity in two-dimensional metals with arbitrary Fermi surface Phys. Rev. B 43 193–201

[75] Stojkovic B P and Pines D 1997 Theory of the longitudinal and Hall conductivities of the cuprate superconductors Phys. Rev. B 55 8576–95

[76] Barman H, Laad M S and Hassan S R 2018 Realization of a ‘two relaxation rates’ in the Hubbard–Falicov–Kimball model Phys. Rev. B 97 075133

[77] Blake M and Donos A 2015 Quantum critical transport and the Hall angle in holographic models Phys. Rev. Lett. 114 021601

[78] Alexandrov A S, Bratkovsky A M and Mott N F 1994 Hall effect and resistivity of high-T$_c$ oxides in the bipolaron model Phys. Rev. Lett. 72 1734–7

[79] Allen S J, Jalan B, Lee S, Ouettel D G, Khalsa G, Jaroszynski J, Stemmer S and MacDonald A H 2013
Conduction-band edge and Shubnikov–de Haas effect in low-electron-density SrTiO$_3$. Phys. Rev. B 88 045114

Wang Z et al 2016 Tailoring the nature and strength of electron–phonon interactions in the SrTiO$_3$(001) 2D electron liquid Nat. Mater. 15 835–9

Raghavan S, Schumann T, Kim H, Zhang J Y, Cain T A and Stember S 2016 High-mobility BaSnO$_3$ grown by oxide molecular beam epitaxy APL Mater. 4 016106

Moriya T and Ueda K 2003 Antiferromagnetic spin fluctuation and superconductivity Rep. Prog. Phys. 66 1299–341

García-Muñoz J L, Rodríguez-Carvajal J, Lacorre P and Torrance J B 1992 Neutron-diffraction study of RNO$_3$ (R = La,Pr,Nd,Sm): electronically induced structural changes across the metal–insulator transition Phys. Rev. B 46 4414–25

Medarde M, Dallera C, Grioni M, Delley B, Vernay F, Raghavan S, Schumann T, Kim H, Zhang J Y, Cain T A and Georgievski B 2016 Tailoring the nature and strength of electron–phonon interactions in the SrTiO$_3$(001) 2D electron liquid Nat. Mater. 15 835–9

Chakraborty B and Allen P B 1979 Boltzmann theory generalized to include band mixing: a possible theory for ‘resistivity saturation’ in metals Phys. Rev. Lett. 42 736–8

Gunnarsson O, Calandra M and Han J E 2003 Colloquium: Saturation of electrical resistivity Rev. Mod. Phys. 75 1085–99

Deng X Y, Mravlje J, Zitko R, Ferrero M, Kotliar G and Georges A 2013 How bad metals turn good: spectroscopic signatures of resilient quasiparticles Phys. Rev. Lett. 110 086401

Hussey N E, Takenaka K and Takagi H 2004 Universality of the Mott–Ioffe–Regel limit in metals Phil. Mag. 84 2847–64

Ioffe A F and Regel A R 1960 Non-crystalline, amorphous and liquid electronic semiconductors Prog. Semicond. 4 237–91

Mott N F 1972 Conduction in non-crystalline systems IX. The minimum metallic conductivity Phil. Mag. 26 1015–26

Licciardello D C and Thouless D J 1975 Constancy of minimum metallic conductivity in two dimensions Phys. Rev. Lett. 35 1475

Caviglia A D, Gariglio S, Reyren N, Jaccard D, Schneider T, Gabay M, Thiel S, Hammerl G, Mannhart J and Triscone J M 2008 Electric field control of the LaAlO$_3$/SrTiO$_3$ interface ground state Nature 456 624–7

King P D C, Wei H I, Nie Y F, Uchida M, Adamo C, Zhu S, He X, Bozovic I, Schlom D G and Shen K M 2011 Atomic-scale control of competing electronic phases in ultrathin LaNiO$_3$, Nat. Nanotechnol. 6 443–7

Schervitz R, Gariglio S, Gabay M, Zubko P, Gilbert M and Triscone J M 2011 Metal–insulator transition in ultrathin LaNiO$_3$ films Phys. Rev. Lett. 106 246403

Yoshimatsu K, Okabe T, Kugamishiro H, Kamoto S, Aizaki S, Fujimori A and Oshima M 2010 Dimensional crossover-driven metal–insulator transition in SrVO$_3$ ultrathin films Phys. Rev. Lett. 104 146401

Son J, Moetakef P, LeBeau J M, Ouellette D, Balents L, Allen S J and Stemmer S 2010 Low-dimensional Mott material: transport in ultrathin epitaxial LaNiO$_3$ films Phys. Rev. Lett. 105 066401

Hwang J, Son J, Zhang J Y, Janotti A, Van de Walle C G and Stemmer S 2013 Structural origins of the properties of rare earth nickelate superlattices Phys. Rev. B 90 060401

Bergmann G 1984 Weak localization in thin films: a time-of-flight experiment with conduction electrons Phys. Rep. 107 1–58

Gurvitch M 1981 Ioffe–Regel criterion and resistivity of metals Phys. Rev. B 24 7404–7

Peil O E, Ferrero M and Georges A 2014 Orbital polarization in strained LaNiO$_3$: structural distortions and correlation effects Phys. Rev. B 90 045128

Wu M et al 2013 Strain and composition dependence of orbital polarization in nickel oxide superlattices Phys. Rev. B 88 125124

Lin X, Rischau C W, Buchauer L, Jaoui A, Fauque B and Behnia K 2017 Metallicity without quasi-particles in room-temperature strontium titanate NPI Quantum Mater. 2 41

Wunderlich W, Ohta H and Kourmoko K 2009 Enhanced effective mass in doped SrTiO$_3$ and related perovskites Physica B 404 2202–12

Eagles D M, Georgiev M and Petrova P C 1996 Explanation for the temperature dependence of plasma frequencies in SrTiO$_3$ using mixed-polaron theory Phys. Rev. B 54 22–5
[121] van Mechelen J L M, van der Marel D, Grimaldi C, Kuzmenko A B, Armitage N P, Reyren N, Hagemann H and Mazin I I 2008 Electron–phonon interaction and charge carrier mass enhancement in SrTiO$_3$ Phys. Rev. Lett. 100 226403

[122] Prange R E and Kadanoff L P 1964 Transport theory for electron–phonon interactions in metals Phys. Rev. 134 A566–80

[123] Devillers M A C 1984 Lifetime of electrons in metals at room temperature Solid State Commun. 49 1019–22

[124] Du X, Tsai S-W, Maslov D L and Hebard A F 2005 Metal–insulator-like behavior in semimetallic bismuth and graphite Phys. Rev. Lett. 94 166601

[125] Bruin J A N, Sakai H, Perry R S and Mackenzie A P 2013 Similarity of scattering rates in metals showing T-linear resistivity Science 339 804–7

[126] Cain T A, Kajdos A P and Stemmer S 2013 La-doped SrTiO$_3$ films with large cryogenic thermoelectric power factors Appl. Phys. Lett. 102 182101

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