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High field transport properties of $La_{2-x}Sr_xCuO_4$ epitaxial thin films

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Abstract. We have studied the temperature dependent resistivity $\rho(T)$ of $La_{2-x}Sr_xCuO_4$ epitaxial thin films in the doping range $0.045 \le x \le 0.25$ in pulsed magnetic fields up to 50 T. The zero-field resistivity $\rho(T)$ of these samples in the pseudogap regime, can be scaled onto one single universal curve in a broad temperature range by using a linear transformation of both temperature and resistivity. The high field data $\rho(T)$ reveal a metal to insulator transition (MIT) at low temperatures, well into the overdoped regime. For samples having $k_F l < 1$, with k_F the Fermi wave vector and l the mean free path, this low temperature insulating behavior of the resistivity is described by the variable range hopping conductivity (VRH). For samples with $k_F l > 1$, the divergence follows $\rho(T) \sim \ln(1/T)$ or a power law, depending upon the Sr-content. We further found that the residual conductivity at the minimum in $\rho(T)$, appearing due to the MIT, follows a linear behavior with respect to the Sr-content. It is argued that the unusual MIT in compounds with $k_F l > 1$, is most probably associated with the pseudogap and the behavior of charge stripes at low temperatures.

PACS. 74.25.Fy Transport properties – 74.25.jb Electronic structure

1 Introduction

A clear insight in the scattering processes dominating the normal state resistivity of layered high-T_c cuprates may provide a clue to the understanding of high-T_c superconductivity itself. A remarkable scaling behavior of the normal state temperature dependent resistivity $\rho(T)$ upon changing the oxygen content has been reported for $YBa_2Cu_3O_{7-\delta}$ (YBCO) [1,2] and $Y_{0.6}Pr_{0.4}Ba_2Cu_3O_4$ [2]. A similar scaling has been obtained for the Hall-coefficient as a function of the temperature in $YBa_2Cu_3O_{7-\delta}$ [2] and underdoped $La_{2-x}Sr_xCuO_4$ [3]. These observations are pointing out that the scattering mechanisms, responsible for the peculiar non-Fermi liquid behavior in the normal state of these underdoped systems, are independent of the hole concentration in the temperature range $T > T_c$. Below the critical temperature T_c, the normal state properties of high-T_c compounds are masked by the presence of superconductivity. Several groups, see *e.g.* [2,4–6], used strong magnetic fields to investigate the normal state, restored in high fields at temperatures below T_c. An insulating ground state, reflected by the presence of an increase of the resistivity when lowering the temperature, could be revealed at low temperatures for several high-T_c systems ($La_{2-x}Sr_xCuO_4$ [4,6], $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ [5], $Y_{0.6}Pr_{0.4}Ba_2Cu_3O_4$ [2]).

In this work, we investigate the high field resistivity of $La_{2-x}Sr_xCuO_4$ (LSCO) epitaxial thin films, conceptually one of the simplest cuprate superconductors, both in the underdoped ($x < 0.15$) and the overdoped ($x > 0.15$) regime in pulsed magnetic fields up to 50 T and in the temperature range from 4.2 K up to room temperature. We will first address the question whether the universal scaling of the normal state resistivity, earlier observed in YBCO [1,2], is also applicable to the LSCO system. Secondly, we will focus on the behavior of the resistivity at low temperatures when superconductivity is suppressed by applying a high magnetic field. Depending on the charge carrier concentration, which is systematically changed through the variation of the Sr-content x, we found (i) a variable range hopping (VRH) like, (ii) a power law like and (iii) a logarithmic divergence of the resistivity when lowering the temperature. To which extent the universal scaling of the resistivity persists down to the low-temperature insulating regime, is discussed in detail. The question whether or not the high field data are a good representative of the normal state is treated.

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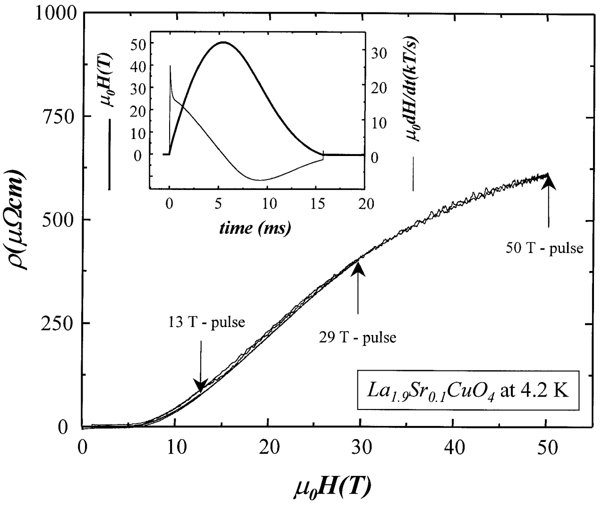


Fig. 1. The field dependent resistivity $\rho(\mu_0H)$ at 4.2 K of a $La_{1.9}Sr_{0.1}CuO_4$ thin film is presented during three field pulses with peak fields of respectively 13 T, 29 T and 50 T. For all the pulses, both traces, taken during increasing and decreasing magnetic field, are plotted. The inset shows the shape of the high magnetic field pulse (thick line) and its derivative with respect to the time (thin line).

2 Experimental details

The $La_{2-x}Sr_xCuO_4$ epitaxial thin films (thickness $\sim$ 150 nm) are prepared, *in situ*, by DC sputtering from stoichiometric targets on $SrTiO_3$ substrates [7]. We studied six different compositions, nominally $x = 0.045$, 0.055, 0.06, 0.1, 0.2 and 0.25. The latter four are superconducting above 1.5 K with a critical temperature T_c (offset) of 2.8 K, 18 K, 22.3 K and 16.5 K, respectively. The reduction of T_c with respect to single crystals is due to a lattice mismatch of about -3% between the c-axis oriented epitaxial thin film and its $SrTiO_3$ substrate along the two in-plane axes a and b [8]. The T_c-values of our samples are in very good agreement with earlier reports on similar thin films [8–10]. The fact that the magnitudes of the resistivity ρ are comparable with the values reported for single crystals, reflects the excellent quality of our thin films. The X-ray and Rutherford Backscattering measurements, carried out on our samples, confirm this quality. The samples are patterned ($1000 \times 100\,\mu$m) for four probe measurements in the transverse geometry ($\mu_0H \perp I$) with the current sent along the ab-plane ($I \parallel ab$) and the magnetic field applied perpendicular to the film ($\mu_0H \parallel c$). The small width (100 μm) and thickness ($\sim$ 150 nm) of the current strip enable the generation of high voltages even at low currents. Gold contacts are evaporated on the samples and wired using silver paint. This procedure results in a contact resistance of less then 5 Ω.

The magnetoresistivity measurements are performed in the pulsed field facility of the Katholieke Universiteit Leuven [11,12] by using a homemade flow-cryostat and 50 T coil. The inset of Figure 1 shows the shape of the field pulse. To obtain the high field transport properties of the $La_{2-x}Sr_xCuO_4$ thin films, a DC technique in combination with a fast transient recorder operating at 1 MHz is used. In general, eddy currents, induced by the high sweep-rate of the magnetic field in the metallic parts of the setup (wiring, cryostat or sample) may heat up the sample during the pulse. To check the implications of these possible heating effects, the following routine tests are performed for all the results reported in this paper. We first compare the results within a set of fixed-temperature pulses with different peak field. The pulse duration is the same for the various pulses hence the sweep rate (and thus the heating) as a function of the field should be different. Figure 1 illustrates that the $\rho(\mu_0H)$ data on $La_{1.9}Sr_{0.1}CuO_4$ at 4.2 K, during a 13 T, 29 T and 50 T pulse, reveal the same behavior. However, a small discrepancy of a few percent between the three data sets can be discerned in the whole field-range. This effect is not caused by sample heating but rather by a small drift of the temperature controller. If the field-pulses are taken at temperatures, which slightly differ (some tens of mK), such differences may occur. Secondly, although the sweep rate is much higher during the rising branch of the pulse (see the inset of Fig. 1), we observe no hysteresis between the traces taken during increasing and decreasing magnetic field (Fig. 1). The fact that the data taken during the rising and the lowering branch of the pulse coincide, is a very strong argument against sample heating. That is why we always present the data for both field sweep branches. Finally, low field pulses reproduce well the results from DC measurements. From these observations we conclude that heating effects do not influence our pulsed field data. This careful check for the presence of possible sample heating effects is especially important when measuring the transport properties of underdoped layered cuprates since these materials reveal a strongly diverging resistivity when lowering the temperature, for example a $d\rho/dT$-value of $\sim -1800\,\mu\Omega$ cm/K is observed in $La_{1.955}Sr_{0.045}CuO_4$ at 4.2 K in zero magnetic field (see the inset of Fig. 3 below). In this case, the slightest heating of the sample during the pulse can artificially lead to negative magnetoresistivity effects. The zero field $\rho(T)$-curves are measured from 1.5 K up to 400 K.

3 Experimental results and discussion

The temperature dependence of the resistivity $\rho(T)$ of $La_{1.9}Sr_{0.1}CuO_4$ ($T_c = 18$ K) at zero field is presented in Figure 2 by the solid line. A linear $\rho(T)$ behavior can be observed above the temperature T^*. Due to a reduced scattering which is the symptom of the opening of the pseudogap in the electronic energy spectrum, a drop in the resistivity shows up below T^*. At intermediate temperatures $T_c < T < T^*$, a superlinear $\rho(T)$ behavior emerges. The shape of the $\rho(T)$ curve, like the one presented in Figure 2, is not only characteristic for $La_{1.9}Sr_{0.1}CuO_4$ but also for other underdoped high T_c cuprates, which is well documented in the literature [2,13]. The successful scaling analysis of the temperature dependent resistivity of YBCO [1,2], which we will extend to the LSCO system, is based on these universal features. In Figure 3 the scaled $\rho(T)$ curve is plotted for

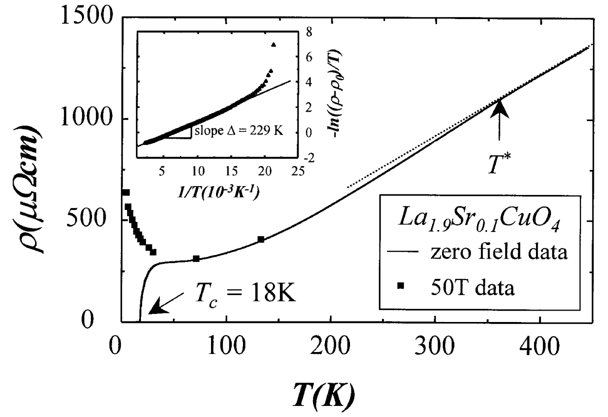


Fig. 2. The full curve gives the resistivity as a function of the temperature, for the $La_{1.9}Sr_{0.1}CuO_4$ compound with a T_c of 18 K, at zero field. The black squares correspond to the resistivity values at 50 T. The resistivity shows a linear temperature dependence above T^*. The inset presents the fit of the experimental data using the 1D quantum conductivity model proposed in [16].

$La_{2-x}Sr_xCuO_4$ with $x = 0.055$, 0.06 and 0.1. The temperature is rescaled with a parameter $\varDelta$ and the resistivity plotted as $(\rho - \rho_0)/(\rho_{2/3\varDelta} - \rho_0)$ where $\rho_{2/3\varDelta}$ is the resistivity at $T = 2/3\varDelta$ and ρ_0 the residual resistivity. The very good scaling for temperatures $T > T_c$, presented in Figure 3, strongly indicates that the transport properties in these samples are dominated by the same underlying scattering mechanisms. The parameter $\varDelta$ defines the energy scale controlling both the linear and the superlinear behavior. The thin films with $x = 0.055$ and 0.06 reveal a negative slope $d\rho/dT$ at low temperatures $T > T_c$, which is associated with the onset of localization effects. The scaling persists in this insulator-like region, although in a narrow temperature range.

The resistivity-curve $\rho(T)$ of the doped double leg spin ladder compound $Sr_{2.5}Ca_{11.5}Cu_{24}O_{41+\delta}$ at a pressure of 8 GPa from reference [14] is added to Figure 3, rescaled both for temperature and resistivity. A striking similarity between the $\rho(T)$ curves of the spin-ladder and the underdoped high-T_c compounds is clearly seen. Spin-ladders share with high T_c's the presence of a gap $\varDelta$ and theories predict that their ground state becomes dominated by superconducting correlations upon doping them with holes [15]. The strong similarities, presented here, are in a good agreement with stripe models for underdoped cuprates. Moreover, the superlinear region $T < T^*$ has been successfully interpreted in the framework of the one-dimensional even-chain Heisenberg AF spin-ladder model [16] leading to the expression

$$\rho(T) = \rho_0 + CT \exp\left(\frac{-\varDelta}{T}\right) \quad (1)$$

with ρ_0 the residual resistivity and C a system-dependent constant. The slope of the $\ln((\rho - \rho_0)/T)$ *versus* $1/T$ linear dependence (shown in the inset of Fig. 2 for sample $La_{1.9}Sr_{0.1}CuO_4$) gives the pseudogap using the residual resistivity ρ_0 as the only fitting parameter. According to the model [16], the pseudogap in high T_c's has analogies with the spin-gap in two-leg ladders. The gap-values for our LSCO compounds (summarized in Tab. 1) are used as parameters for the scaling of the temperature axis in Figure 3. The T^*-values for the different samples, for example, can serve as good scaling parameters as well, since they are equal to the set of gap-values $\varDelta$, multiplied with a factor. For most of the samples, the gap $\varDelta$ exceeds room temperature and lies out of the temperature window of our experiments. This is the reason why we used $\rho_{2/3\varDelta}$ to rescale the resistivity in Figure 3 but, in principle, $\rho_\varDelta$ would be a good choice too. It is important to notice that the scaling behavior presented in Figure 3 is very general and not restricted to any specific theoretical model describing the gap or the temperature dependent resistivity.

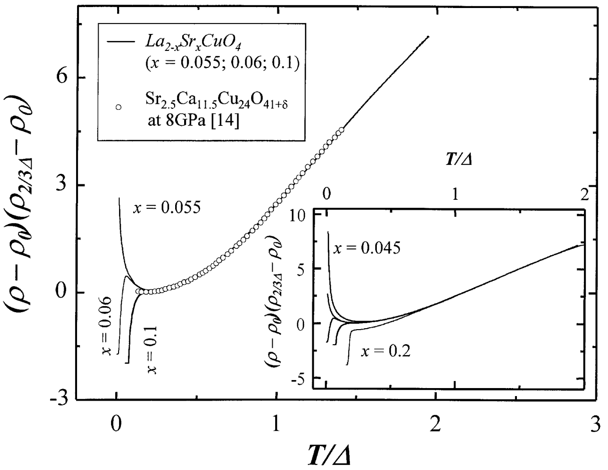
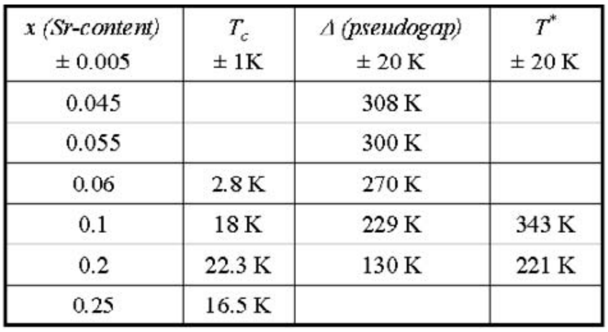


Fig. 3. The temperature dependence of the resistivity $\rho(T)$, rescaled linearly in temperature and resistivity, is given for $La_{2-x}Sr_xCuO_4$ with $x = 0.055$, 0.06 and 0.1. The corresponding data for the doped double leg spin ladder compound $Sr_{2.5}Ca_{11.5}Cu_{24}O_{41+\delta}$ at a pressure of 8 GPa, taken from reference [14], are added to the graph. The inset includes the rescaled data of the strongly underdoped $La_{1.955}Sr_{0.045}CuO_4$ and the overdoped $La_{1.8}Sr_{0.2}CuO_4$.

Table 1. The Sr content x, the critical temperature T_c, the pseudogap value D and the crossover temperature T^* are tabulated for the different $La_{2-x}Sr_xCuO_4$ samples.



x (Sr-content) ± 0.005	T_c ± 1K	*Δ (pseudogap)* ± 20 K	T^* ± 20 K
0.045		308 K	
0.055		300 K	
0.06	2.8 K	270 K	
0.1	18 K	229 K	343 K
0.2	22.3 K	130 K	221 K
0.25	16.5 K		

The inset of Figure 3 includes the rescaled data of the strongly underdoped $La_{1.955}Sr_{0.045}CuO_4$ and the overdoped $La_{1.8}Sr_{0.2}CuO_4$. Although the resistivity data

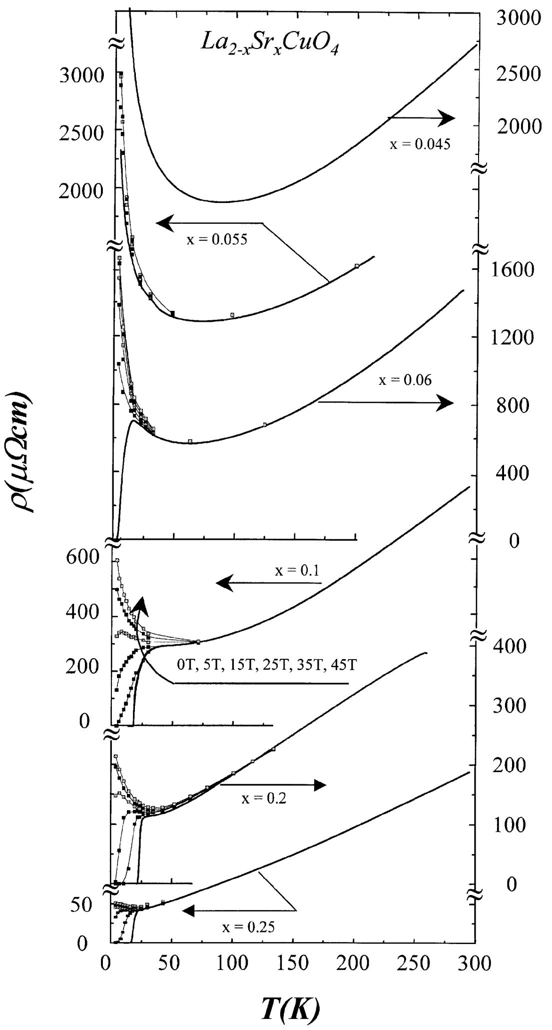


Fig. 4. The resistivity as a function of the temperature is plotted at zero field, 5 T, 15 T, 25 T, 35 T and 45 T for the $La_{2-x}Sr_xCuO_4$ thin films with $x = 0.045$, 0.055, 0.06, 0.1, 0.2 and 0.25.

for these compounds follow the universal curve in a very extended temperature range, they deviate at low temperatures (below $T/\Delta = 0.3$ and $T/\Delta = 0.6$ for $La_{1.955}Sr_{0.045}CuO_4$ and $La_{1.8}Sr_{0.2}CuO_4$ respectively). Our strongest overdoped sample, $La_{1.75}Sr_{0.25}CuO_4$, shows a weak power-law behavior (power 1.2) of the resistivity down to just above T_c, which did not allow us to find a suitable scaling parameter. The possible origin of these discrepancies will be discussed below in the paper.

In order to get a better insight into the low temperature ground state of our samples, the resistivity has been studied in pulsed magnetic fields up to 50 T. The temperature dependence of the resistivity $\rho(T)$ at fixed high magnetic fields can be determined for all the studied compounds like shown in Figure 4. All samples, which follow the universal scaling of the normal state transport properties (and, as a consequence, reveal a pseudogap), exhibit a minimum in $\rho(T)$ and a crossover from metallic to insulator-like behavior upon a temperature decrease. In the literature, a low temperature insulating behavior persisting up to optimal doping is reported both for LSCO single crystals [6] and for the electron-doped superconductor $Pr_{2-x}Ce_xCuO_4$ [17]. In $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$, it disappears at 1/8 hole doping, in the underdoped regime [5]. *Our results, on the other hand, show a metal to insulator-like transition in a* $La_{1.75}Sr_{0.25}CuO_4$ *thin film, stretching well into the overdoped regime.*

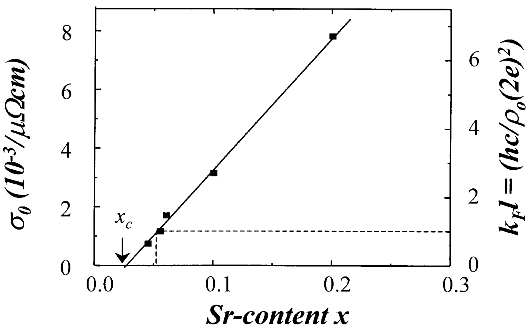


Fig. 5. The linear dependence of $k_Fl(= hc/\rho_0(2e)^2)$, where k_F is the Fermi wave vector, l the mean free path and $2e$ the charge, is shown as a function of the Sr-content x. The conductivity at the minimum in the $\rho(T)$-curves, σ_0, reveals the same dependence. At the critical Sr-content x_c, k_Fl and σ_0 are extrapolated to zero. The dashed lines indicate the insulator to superconductor transition.

The magnitude of the residual resistivity ρ_0, obtained from the earlier presented stripe model [16], agrees very well with the value of the minimum in the temperature dependent resistivity $\rho(T)$, revealed by the high field measurements. Using a free electron model for layered two-dimensional systems, ρ_0 immediately gives $k_Fl = hc/\rho_0 e^2$, where $c = 13.2$ Å is the length of the unit cell in the c direction. The insulator to superconductor transition in our samples takes place around $k_Fl = 4$, corresponding to a sheet resistance of $h/4e^2$ per CuO_2 bilayer. The observed superconductor to insulator crossover is similar to that shown by conventional superconducting ultrathin films [18] and high-T_c ultrathin films [19], which give up superconductivity as soon as their sheet resistance falls below a value close to $h/4e^2$, realized by decreasing the film thickness. The same threshold value is also observed for the carrier-concentration-driven superconductor to insulator transition in YBa_2CuO_4 single crystals [20]. Possibly, this transition can be ascribed to hole pair localization [21]. We therefore adopted the expression for k_Fl to $k_Fl = hc/\rho_0(2e)^2$.

Figure 5 shows a linear dependence of k_Fl and σ_0 as a function of the Sr-content. For doped semiconductors, it is well known that the conductivity in the vicinity of the metal to insulator transition obeys:

$$\sigma_0 \sim (x - x_c)^\gamma \tag{2}$$

with γ a critical exponent which determines the character of the transition. Quitmann *et al.* [22] extrapolated this scaling behavior to high-T_c systems and used the same expression for the conductivity in the vicinity of the superconductor to insulator transition. Our data reveal a critical concentration $x_c = 0.025$ and $\gamma = 1$, in

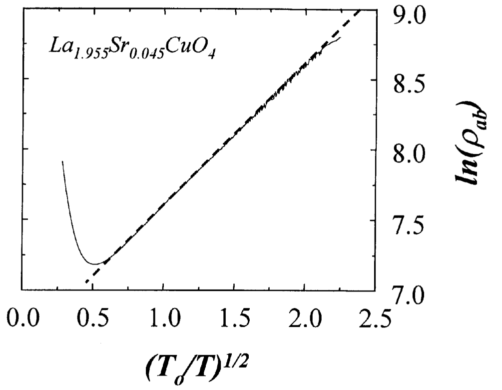


Fig. 6. The variable range hopping conductivity can describe the low-temperature insulating behavior of the resistivity in $La_{1.955}Sr_{0.045}CuO_4$. The fit with $\rho(T) = A^* \exp\left(\frac{T_0}{T}\right)^\alpha$ is shown leading to $A = 733\,\mu\Omega$cm, $T_0 = 23.4$ K and $\alpha = 1/2$.

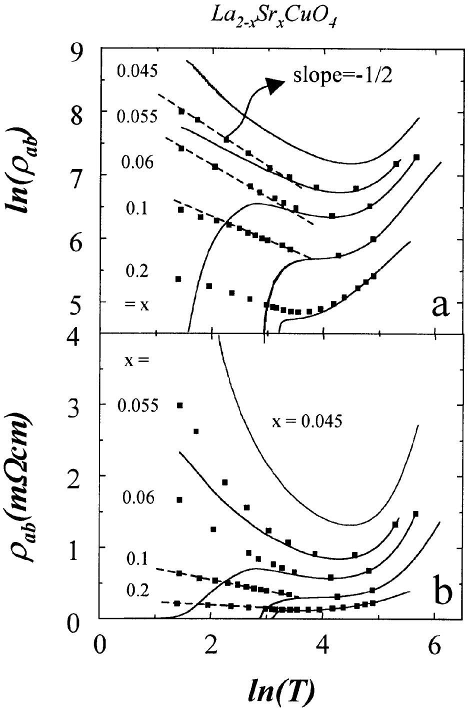


Fig. 7. The resistivity as a function of the temperature at zero field (full line) and at 45 T (full squares) are shown for $La_{2-x}Sr_xCuO_4$ with $x = 0.045$, 0.055, 0.06, 0.1 and 0.2 in a ($\ln(\rho)$ *vs.* $\ln(T)$)-plot (*a*) and in a (ρ *vs.* $\ln(T)$)-plot (b) in order to distinguish between a power-law and a logarithmic behavior of the resistivity with respect to the temperature.

good agreement with the results of Quitmann *et al.* on $Bi_2Sr_2(Ca_zY_{1-z})Cu_2O_{8+y}$ [22]. For $\gamma = 1$, theories [23] predict a transition driven by long range interactions in the presence of spin-flip scattering. The $\gamma = 1$ value is also found for amorphous metals [24] where disorder underlies the transition. It is however a priori not evident at all that a model for traditional semiconductors is applicable to high T_c's. For example, the linear behavior of σ_0 with respect to the carrier concentration x, may be associated with the inverse of the interstripe distance developing linearly in x.

The above-cited ideas may clarify the character of the superconductor to insulator transition but don't explain why a metal to insulator transition takes place in rather clean systems with $k_F l > 1$. The strongly underdoped compound $La_{1.955}Sr_{0.045}CuO_4$ lies below the Ioffe-Regel limit $k_F l = 1$ (at $x = 0.05$) and reveals a disorder induced metal to insulator transition upon a decrease in temperature, characterized by a variable range hopping conductivity:

$$\rho(T) = A^* \exp\left(\frac{T_0}{T}\right)^\alpha . \tag{3}$$

This is convincingly demonstrated in Figure 6, showing a fit using the above expression with $A = 733$ $\mu\Omega$cm, $T_0 = 23.4$ K and $\alpha = 1/2$. The exponent $\alpha = 1/2$ is determined by the dimensionality (D) of the system and the shape of the density of states $g(E)$ near the Fermi-level ($g(E) \propto (E - E_F)^n$):

$$\alpha = \frac{n+1}{n+D+1} \cdot \tag{4}$$

In the simple case $n = 0$ [25], $\alpha = 1/2$ yields $D = 1$. When for example a Coulomb gap develops around the Fermi-level [26], the dimensionality of the system can be 2 or 3 as well, to explain the experimental value $\alpha = 1/2$. $La_{1.955}Sr_{0.045}CuO_4$ has, compared to the other pseudogapped samples, completely different transport properties at low temperatures: it shows no superconductivity, no large positive magnetoresistivity effects (Fig. 1) and $k_F l < 1$. The lack of a universal scaling behavior for its zero-field low temperature resistivity, as presented in the inset of Figure 3, is therefore not surprising. $La_{1.945}Sr_{0.055}CuO_4$ ($k_F l = 1.05$) lies very close to the insulator to superconductor transition at $k_F l = 1$ but, in view of its large positive magnetoresistivity at low temperatures (Fig. 4), the sample becomes most probably superconducting at temperatures below 1.5 K.

To be able to judge about a universal behavior of the resistivity in the insulator-like regime for superconducting samples with a pseudogap, we plotted their resistivities in two ways: $\ln(\rho_{ab})$ *versus* $\ln(T)$ (Fig. 7a) and ρ_{ab} *versus* $\ln(T)$ (Fig. 7b) both at zero field and at 45 T. Figures 7a and b show that it is very difficult to distinguish between a power-law like and a logarithmic divergence of the resistivity at low temperatures. The agreement of the high field $\rho(T)$ data of $La_{1.945}Sr_{0.055}CuO_4$ and $La_{1.94}Sr_{0.06}CuO_4$ with a power-law (power = $-1/2$) is better than the correspondence with a $\ln(1/T)$ divergence. The deviation from a power law at the lowest temperatures for $La_{1.9}Sr_{0.1}CuO_4$ and $La_{1.8}Sr_{0.2}CuO_4$ may be due to an insufficient field. However, the high field data of the latter two samples can be much better described by $\ln(1/T)$. Currently, no consensus exists on the nature of the localization of the charge carriers. It is again clear from Figures 7a–b that the strongly underdoped sample

$La_{1.955}Sr_{0.045}CuO_4$ is different in that sense from the other samples.

The low-temperature insulating behavior is only observed in samples with a pseudogap. The existence of a pseudogap in layered cuprates is commonly accepted and confirmed by several experiments (for a review see [13]). The real nature of the gap, on the other hand, is still a controversial issue. One of the possible scenarios associates the pseudogap with the existence of electronic pair states below T^* [27,28]. These pairs might originate from a phase separation appearing below a certain critical temperature. Dynamical 'rivers of charges' are generated on a microscopic scale, separated by insulating antiferromagnetic stripes. The pairing behavior is, in this case, the consequence of the presence of a spin gap in the antiferromagnetic stripes since the gap makes pair hopping between the charge rich and antiferromagnetic regions energetically more favorable than single particle hopping; *i.e.* some sort of magnetic proximity effect takes place. Superconductivity is established when there is a phase coherent motion of the pairs from stripe to stripe.

The theory [27] defines two characteristic temperatures: the first is the temperature below which pairing becomes locally significant, the second corresponds to the onset of phase coherence. Classical phase fluctuations, present in underdoped systems, suppress the latter temperature far below the temperature where pairing first occurs. Classical phase fluctuations are more important in superconductors with a low superfluid density. This explains why the pre-pairing effects are much more apparent in the underdoped cuprates rather then in classical superconductors or in the overdoped case. The ideas outlined in [27] may serve as an explanation for the fact that the overdoped $La_{1.8}Sr_{0.2}CuO_4$ does not follow the universal scaling of the resistivity down to the lowest temperatures. The pseudogap, in this compound, is most probably formed at a temperature below the temperature where phase coherence may occur.

The stripe picture of the pseudogap gains a growing experimental support. Dynamical magnetic antiferromagnetic (AF) correlations are revealed by neutron scattering studies on LSCO, with an inverse interstripe distance, which depends linearly on the Sr-content [29]. Scanning tunneling spectroscopy clearly demonstrated that the pseudogap evolves into the superconducting gap at low temperatures [30]. Moreover, ARPES data [31,32] indicate that the pseudogap and the superconducting gap both have *d*-wave symmetry.

It is likely that the pseudogap and the presence of stripes and precursor pairs define the nature of the unusual metal to insulator transition in our superconducting LSCO thin films. Possibly the stripes get fragmented at low temperatures. In this respect, we would also like to mention the recent results of Segawa and Ando [33] who found a strong enhancement of the low temperature insulating behavior of the resistivity in YBCO upon doping with Zn in ordered systems with $k_F l > 1$. Zn is known to produce a large residual resistivity [34] and to disturb locally the AF correlations. It is possible that the disorder, induced in our thin films by a tensile strain from the substrate, expands the insulating regime with respect to that in single crystals as well.

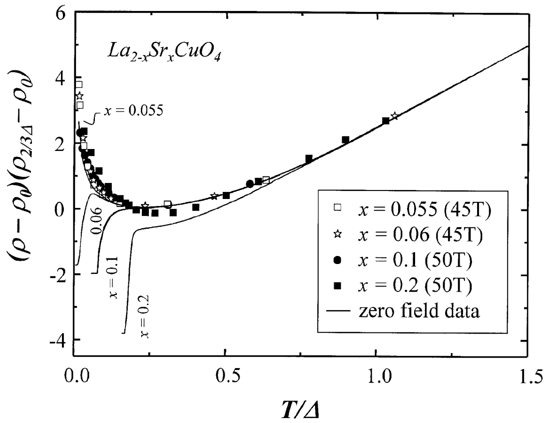


Fig. 8. The temperature dependence of the resistivity $\rho(T)$, rescaled linearly in temperature and resistivity, is shown for $La_{2-x}Sr_xCuO_4$ with $x = 0.055$, 0.06, 0.1 and 0.2 at zero field (full lines) and at high fields (symbols).

If the picture of a precursory behavior towards superconductivity is true, the $\ln(1/T)$ divergence, revealed in pulsed magnetic fields up to 60 T [2,4,5], *does not necessarily mimic the behavior of the high-T_c electron system at zero magnetic field in the absence of superconductivity* like it was stated in [6]. The ARPES research of Loeser *et al.* on the pseudogap in $Bi_2Sr_2CaCu_2O_{8+\delta}$ [31] revealed a binding energy of 75 meV in the pairs. A magnetic field of about 1300 T would be needed to destroy them. In the stripe picture, T^* rather then T_c reflects the critical temperature in pseudogapped and underdoped superconductors [27,30]. This would lead to a paramagnetic limit of $\mu_0 H_p = 500$ T for our LSCO films. Furthermore, the magnetoresistivity data for $La_{1.9}Sr_{0.1}CuO_4$, presented in Figure 1, do not show neither a clearly marked critical field nor a saturation at high fields. The origin of the unusual $\ln(1/T)$ dependence lies therefore most probably in the behavior of the stripes and the precursor pairs in a magnetic field.

The above considerations lead to the conclusion that a universal scaling of the zero field transport properties has been observed for underdoped superconducting systems down into the insulating temperature regime. The $La_{1.945}Sr_{0.055}CuO_4$ reveals, at zero field, a power law divergence of the resistivity when lowering the temperature. Since this sample is situated on the superconducting side, but very close the insulator to superconductor transition, it may be a very good representative of the ground state. $La_{1.945}Sr_{0.055}CuO_4$ and $La_{1.94}Sr_{0.06}CuO_4$ also show a power law behavior at 45 T. For $La_{1.9}Sr_{0.1}CuO_4$ and $La_{1.8}Sr_{0.2}CuO_4$, a logarithmic divergence of the resistivity is found in high fields. The universality of the low temperature $\rho(T)$ behavior therefore does not hold in high fields (Fig. 8).

4 Summary

In summary, we investigated the scaling of the normal state transport properties for LSCO epitaxial thin films from the strongly underdoped regime up to the overdoped regime both in zero magnetic field and in pulsed magnetic fields up to 50 T. A universal scaling has been found for underdoped superconducting films in zero magnetic field. Because the high field data revealed, depending on the Sr-content, both a power-law and a $\ln(1/T)$ divergence of the resistivity at low temperatures, no universal behavior of $\rho(T)$ has been found at high fields in this temperature range. It has been argued that the 50 T *data are not a good representative of the normal state in the absence of a magnetic field.* The low temperature metal-insulator transition in the LSCO films, whether field induced or not, is most probably associated with the existence of a pseudogap, charge stripes and precursor pair states above T_c. A linear dependence of the residual conductivity *versus* the Sr-content has been found in the pseudogapped samples.

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