Noise Spectroscopy Investigation of Interplay Between Quantum Interference Effects and Superconductivity in Infinite Layer Cuprates

C. Barone, A. Galdi, C. Sacco, P. Orgiani, D. G. Schlom, S. Pagano, and L. Maritato

***Abstract*—The interplay between quantum interference effects and superconductivity has been investigated in infinite layer $Sr_{1-x}La_xCuO_{2\pm\delta}$ thin films by using a combination of standard dc electric transport measurements and noise characterization. A marked resistivity upturn at a temperature of 110 K has been observed in underdoped samples, which also showed a superconductive transition at about 25 K. The resistivity behavior has been attributed to weak localization and has been investigated by detailed low-frequency voltage-spectral density measurements. In particular, peculiar linear dependence of the $1/f$ noise on the bias current is found in the weak-localization regime, whereas the usual quadratic dependence of the $1/f$ component occurs in the superconducting and metallic regions.**

***Index Terms*—Electric noise, infinite layer superconductors, metal–insulator transitions, voltage fluctuations.**

I. Introduction

THE nature of electric transport in the normal-state of electron-doped cuprates is still debated in details by the scientific community. A scattering mechanism, electron-electron type, supported by a T^2 power-law at temperatures up to 250 K is commonly considered [1]. Alternatively, a local spin-fluctuation process is indicated as the major scattering phenomenon [2]. In all the reported works on this subject, however, the intermediate temperature region between 50 and 150 K is not accurately discussed, possibly because it is not fully understood. More specifically, around 100 K under-doped samples often show a sizable increase of the resistivity, whose origin has been tentatively attributed to weak localization (WL) [3]. As a matter of fact, a conclusive explanation of the resistivity upturn and the consequent crossover from a metallic to an insulating phase has not been provided, mainly due to an ambiguity in the definition of the effective conducting layer thickness of electron-doped cuprates.

In order to remove this thickness limitation, which could be very important to detect the type of metal-insulator transition realized in practice, infinite layer (IL) $Sr_{1-x}La_xCuO_{2\pm\delta}$ (SLCO) thin films have been investigated and the experimental results are reported in this paper. A very sensitive and non-destructive technique, such as electric noise, has been used to analyze the samples, because it is capable to reveal a strict connection between WL effects and specific properties of the low-frequency $1/f$ noise. In particular, a linear dependence of the voltage-spectral density on the bias current is observed in systems undergoing a WL transition. This distinctive feature has been reported for high-T_c superconducting cuprates [4], manganites [5], and more recently ultrathin metallic films [6]. Here, a similar behavior has been found for the investigated SLCO samples, giving a strong confirmation on the presence of quantum conduction mechanisms in the temperature region below 100 K. The full understanding of electric transport is fundamental for any application of superconductors, especially in the case of high-T_c materials (HTS). Therefore, IL-SLCO, having the simplest structure and highest T_c among the electron-doped HTS, is particularly interesting for possible electronic and transport applications.

In Section II the sample fabrication, as well as the experimental procedures are reported. In Section III, the experimental results on dc transport and noise characterization are discussed. The conclusions are given in Section IV.

II. Experimental

The SLCO films were grown on (110)-oriented $GdScO_3$ (GSO) substrates in a molecular beam epitaxy system, using a shuttered layer-by-layer deposition process in purified O_3. More detailed information, regarding the sample fabrication and structural properties, are reported in [7]. In brief, x-ray diffraction analysis always indicated the preferential c-axis orientation along the substrate crystallographic direction, without any sign of secondary phases. Moreover, a fully-strained condition of the films to the underlying substrates was also confirmed by rocking curve measurements [7].

The heavy ion La/Sr chemical ratio x and oxygen content δ were varied in order to obtain an expected electron doping level

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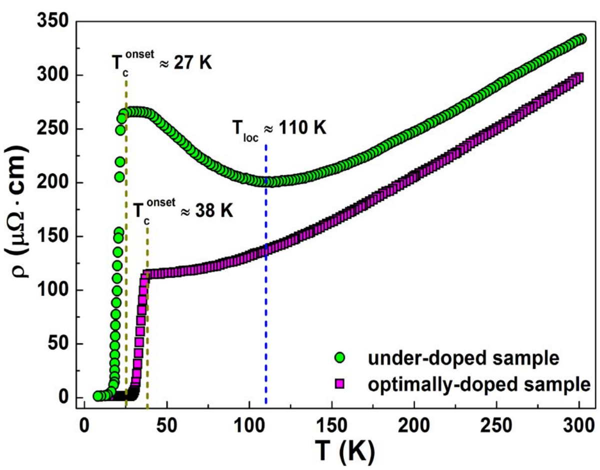

Fig. 1. Resistivity temperature dependence of two selected SLCO samples: (green circles) under-doped and (magenta squares) optimally-doped. The values of the localization temperature $T_{\rm loc}$ and the onset of superconductivity $T_c^{\rm onset}$ are also reported.

n from 0.05 (under-doped samples) to 0.10 (optimally-doped samples). It is important to underline that, for electron-doped IL cuprates, the onset of the superconducting regime is reported to occur for $n \approx 0.04$, while the optimal doping is usually observed for $n = 0.10$ electron per CuO_2 plane [1].

All the experimental investigations were performed in closed-cycle refrigerator systems, operating in the 8–325 K range, with a temperature stabilization better than 0.1 K. Electrical transport and noise measurements were made in a four-probe contact configuration with the use of a low-noise instrumentation. In order to minimize the presence of spurious components in the spectral traces of the samples, the experimental setup was appropriately arranged. A specific procedure, described in detail in [8], was developed to determine and remove contact noise contributions, a possible source of artifacts in this type of experiments.

III. Results and Discussion

The presence of quantum interference effects (QIEs) has been largely observed in the low-temperature transport processes of several disordered electronic systems [9]. However, available studies on localization phenomena are rare in electron-doped cuprates. For this type of compounds, in the case of high quality thin films, it is possible to discriminate the physical mechanism producing QIEs, such as Coulomb interactions, WL effects, and dimensionality (i.e., three-dimensional 3D and/or two-dimensional 2D behaviors). In order to better investigate this aspect, the temperature dependence of the resistivity has been measured for SLCO under-doped samples, which show the occurrence of a strong insulating state below a localization temperature $T_{\rm loc} \approx 110$ K (see, for details, the green circles in Fig. 1). The experimental data indicate the clear coexistence of a metallic (M) and insulating (I) phases, thus suggesting an interpretation of the resistivity behavior in terms of the following linear combination

$$\rho(T) = f \cdot \rho_M(T) + (1 - f) \cdot \rho_I(T) \qquad (1)$$

where ρ_M and ρ_I are the metallic and localization terms, respectively, and f is the phase-separation distribution function. As expected for a spin-fluctuation regime [10], a linear-T dependence is observed for ρ_M, without any transition to a different power-law dependency (e.g., T^2 or T^3) down to low temperatures. Regarding the ρ_I insulating resistivity, several localization phenomena have been considered, ranging from Mott variable-range-hopping to Kondo and WL effects. An accurate statistical analysis reveals that the 3D WL formula better fits the data, producing an unexpected result for IL systems, whose structure is usually assumed to be formed by weakly-coupled 2D-sheets [1].

The existence of QIEs does not prevent the occurrence of the superconductivity in under-doped samples, which show, as evident in Fig. 1, a superconducting onset temperature $T_c^{\rm onset} \approx 27$ K. Conversely, as the optimally-doped regime is approached, by increasing the carrier concentration, the resistivity upturn becomes more and more shallow, until its disappearance, and the superconducting onset reaches the value of 38 K (see, for details, the magenta squares in Fig. 1). It is important to underline, here, that the insulating term in (1) does not abruptly vanish for optimally-doped thin films, rather tends to be weaker and weaker as the metal-like behavior becomes stronger.

The effective presence of a quantum transport phenomenon can be probed by magnetoresistance measurements. Unfortunately, this type of investigations has to be excluded for the SLCO system, since the superconducting transition makes unaccessible the low-temperature region below 10 K, where usually the QIE contribution to magnetoresistance is dominant. In alternative, it has been recently shown that a specific and universal low-frequency $1/f$ noise occurs when QIEs are established [4]–[6]. In particular, the amplitude of voltage fluctuations depends linearly on the bias current I in the WL regime, while the usual quadratic behavior is observed far from the WL region. This anomalous fluctuation mechanism, whose explanation has been given in terms of nonequilibrium universal conductance fluctuations [5], is a material-independent feature only associated with WL [6]. As a consequence, the electric noise spectroscopy is a simple diagnostic technique to detect WL effects.

The frequency dependence of the voltage-spectral density S_V of a typical under-doped SLCO sample here tested is shown in Fig. 2 at different temperatures, covering the whole investigated range between 10 and 300 K. The well-known $1/f$ noise component is clearly dominant when a current is supplied, while a flat background spectrum, corresponding to the thermal Johnson noise added to the electronic chain noise 1.4×10^{-17} V^2/Hz, is visible at zero bias (see the black traces in Fig. 2). The amplitude of this $1/f$ noise has been evaluated at a reference frequency of 90 Hz, and its bias current and temperature dependencies are shown in Fig. 3 (left panel). From the three-dimensional plot, a change in the noise behavior is evident near $T_{\rm loc}$ (110 K). Moreover, a noise peak, due to the fluctuation of the superconducting percolation network [11], is also observed at $T_c^{\rm onset}$ with a less pronounced level reduction below the superconducting transition (21 K).

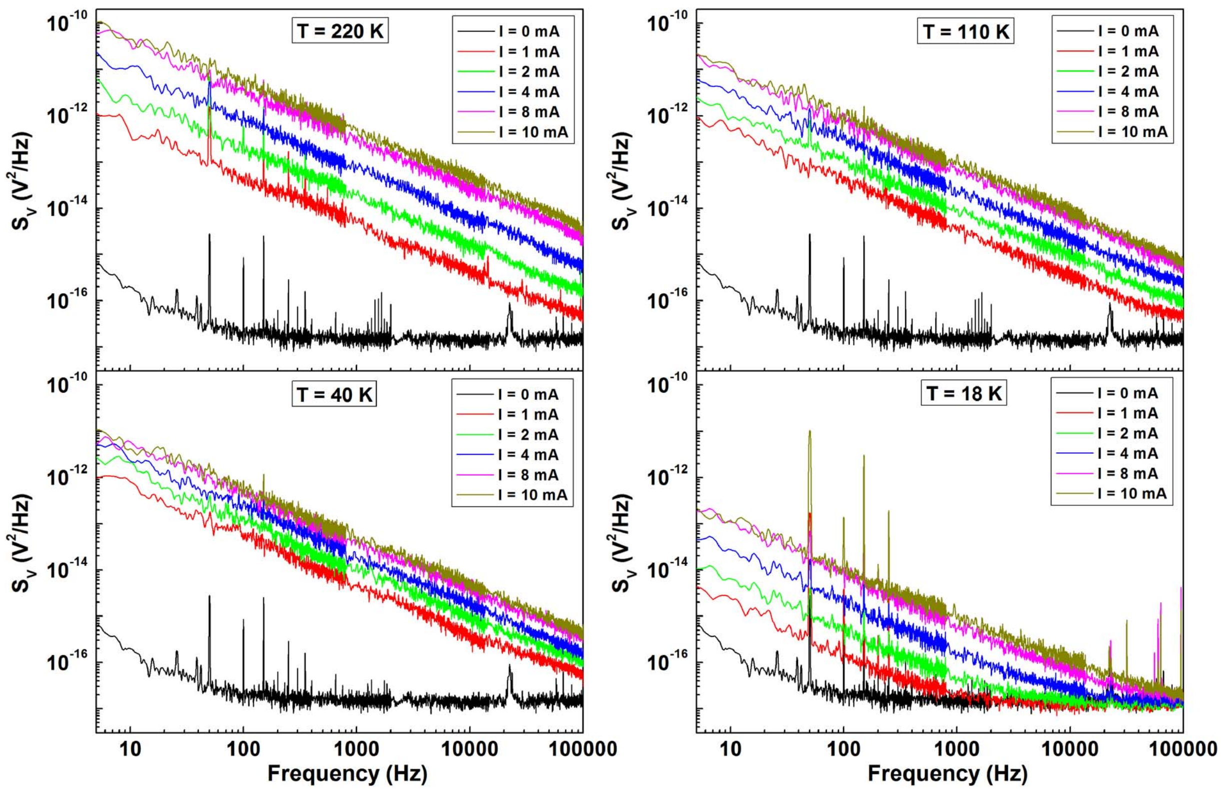

Fig. 2. Low-frequency voltage-noise spectra of an under-doped SLCO investigated sample at different bias current values and temperatures. The data refer to characteristic regions from the electrical transport point of view: metallic (220 K), metal–insulator transition (110 K), weak-localization (40 K), and superconducting (18 K).

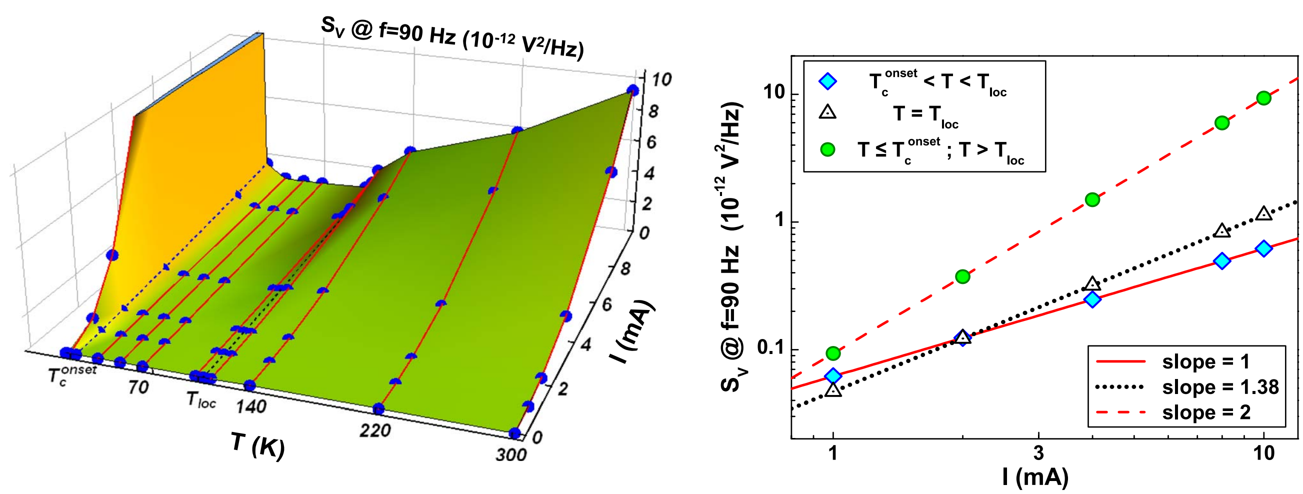

Fig. 3. The $1/f$ noise amplitude is shown as a function of bias current and temperature for an under-doped SLCO sample in the left panel. The same bias current dependence is reported in the right panel in three characteristic electric transport regions (below, at, and above T_{loc}). The lines represent different power exponents.

In order to obtain more information, the current dependence of the voltage noise can be reproduced in terms of a simple power-law expression as

$$S_V(90\ \mathrm{Hz}, I, T) = S_0(T) \cdot I^{\eta(T)} \qquad (2)$$

where S_0 is a temperature-dependent proportionality factor, and η is the current power exponent. The best fitting curves by using (2) are shown in Fig. 3 (right panel), where a variation of the slope value η from 2 to 1 is visible in the temperature region between T_{loc} and T_c^{onset}. An equivalent analysis of the $1/f$ noise can be performed with a parabolic functional form as

$$S_V(90\ \mathrm{Hz}, I, T) = a_2(T) \cdot I^2 + a_1(T) \cdot I + a_0(T) \qquad (3)$$

where a_2, a_1, and a_0 are temperature-dependent coefficients. These fitting parameters are reported in Table I for the same temperatures of Fig. 2, giving precise indications on the transport mechanism and the origin of charge carrier fluctuations in the investigated SLCO under-doped compounds. In particular,

TABLE I
PARABOLIC FITTING PARAMETERS

Temperature (K)	a_2 ($V^2 \cdot Hz^{-1} \cdot mA^{-2}$)	a_1 ($V^2 \cdot Hz^{-1} \cdot mA^{-1}$)	a_0 ($V^2 \cdot Hz^{-1}$)
220	$(5.8291 \pm 0.0002) \times 10^{-14}$	$(1 \pm 3) \times 10^{-16}$	$(1.44 \pm 0.02) \times 10^{-17}$
110	$(5.8 \pm 0.4) \times 10^{-15}$	$(5.5 \pm 0.4) \times 10^{-14}$	$(1.44 \pm 0.02) \times 10^{-17}$
40	$(9 \pm 12) \times 10^{-17}$	$(6.206 \pm 0.009) \times 10^{-14}$	$(1.44 \pm 0.02) \times 10^{-17}$
18	$(1.285 \pm 0.003) \times 10^{-16}$	$(2 \pm 4) \times 10^{-17}$	$(1.44 \pm 0.02) \times 10^{-17}$

Best fitting values of the parameters in (3) at the same temperatures of Fig. 2.

standard resistance fluctuations, whose contribution is proportional to I^2 [11], are the noise source when the system behaves as a metal at high temperatures and below the superconducting transition (see significantly nonzero values of a_2 in Table I). Conversely, the appearance of a linear bias dependence of the $1/f$ noise (large a_1 parameter) is directly related to the occurrence of QIEs. The simultaneous presence of the quadratic and linear terms is a characteristic feature of the two transition regions near $T_{\rm loc}$ and $T_c^{\rm onset}$.

In the case of optimally-doped compounds, no upturn of the resistivity is observed at low temperature, and, consequently, no anomalous noise behavior is expected, as already verified for another electron-doped material [4], [12].

IV. CONCLUSION

The analysis here performed in terms of dc and ac measurements indicates that the spin-fluctuation regime dominates the metallic-like normal-state of electron-doped cuprates. The electronic correlations, instead, determine the arising of low-temperature quantum interference effects, which rule the metal-insulator transition in the intermediate temperature region. This is well evidenced by investigating the charge carrier associated noise, characterized by a peculiar crossover from a I to a I^2 dependence. Conversely, in the metallic and superconducting regimes no evidence of unusual noise-spectral density behavior is observed.

Further studies are needed to better clarify the existence of symmetry in the phase-diagram for both hole-doped and electron-doped cuprates as a function of doping.

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