The presence of charge stripes in strongly underdoped La$_{2-x}$Sr$_x$CuO$_4$ single crystals

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We have measured the $ab$-plane resistivity of La$_{2-x}$Sr$_x$CuO$_4$ single crystals with small Sr content ($x=0.052 \pm 0.007$) between 4.2 and 300 K by using the AC Van der Pauw technique. As recently suggested by Ichikawa et al., the deviation from the linearity of the $\rho_{ab}(T)$ curve starting at a temperature $T_{ch}$ can be interpreted as due to a progressive slowing down of the fluctuations of pre-formed charge stripes. An electronic transition of the stripes to a more ordered phase could instead be responsible for some very sharp anomalies present in the $\rho_{ab}(T)$ of superconducting samples just above $T_c$.

There is a growing experimental evidence for the existence of charge stripes in La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) and the related compounds obtained by substitutions. Successive ordering transitions of these stripes, which seem to have a metallic character, possibly occur when the temperature is lowered. One would expect that, in superconducting samples, the phase transitions of the stripes occurring above $T_c$ leave a mark on the electrical resistivity. In the present work, we study the in-plane resistivity $\rho_{ab}(T)$ of strongly underdoped single crystals of LSCO, which exhibits, besides the usual features previously observed, an anomalous peak just above $T_c$. We relate it to an electronic transition of the stripes to a more ordered phase.

We carefully investigated the temperature dependence of the $ab$-plane resistivity of LSCO single crystals with small Sr doping ($0.052 \leq x \leq 0.075$). The crystals, having typical dimensions of about $1 \times 1 \times 0.3$ mm$^3$, were grown by slowly cooling a non-stoichiometric melt. The chemical composition of every crystal was determined by means of EDS microprobe analysis and only crystals having a homogeneous Sr content were selected. In order to increase the precision of the $ab$-plane measurement, we used an AC version of the standard four-probes eight-measure Van der Pauw method injecting in the crystals AC currents of 100 $\div$ 300 $\mu$A at 133 Hz. Details on the experimental technique are given elsewhere. Fig. 1 shows the results. The crystals with $x=0.052$ are not superconducting and show a low-temperature semiconducting-like behaviour of the resistivity, apart from an anomalous local maximum at about 25 K (curve a in Fig. 1). The crystals with $x=0.06$ and 0.075 show well-defined superconducting transitions with midpoints at $T_c=6.7$ K ($\Delta T_c=0.6$ K) and $T_c=8.9$ K ($\Delta T_c=2.2$ K), respectively (curves b and c). However, very sharp anomalous peaks are present at temperatures about 2 K greater than $T_c$. The inset of Fig. 1 shows these peaks in greater detail. No anomalies are present in the AC susceptibility of the same crystals.

We first discuss the general behaviour of the resistivity curves. The $\rho_{ab}(T)$ at $150 < T < 300$ K is almost perfectly linear. We then fitted the resistivity in this region by using a linear model: $\rho_{ab}(T) = \alpha T + \beta$. Following a recent paper of Ichikawa et al., we calculated the normalized resistivity $\rho_{ab}(T)/\rho(T)$. The results for the superconducting samples are shown in Fig. 2. In Ref. 3 the deviations of the $\rho_{ab}(T)$ from the lin-
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Figure 1. The $ab$-plane resistivity of our LSCO samples with $x = 0.052$, 0.06 and 0.075 (curves a, b and c, respectively). The inset shows an enlargement of the low-temperature part of curves b and c.

carity exceeding a certain threshold (dependent on $x$) have been associated to the localization of pre-formed stripes, which occurs at a temperature $T_{ch}$ independently determined by Cu NQR measurements [3]. This correlation has been observed in Nd-substituted crystals but also in crystals without Nd, having $x$=0.10 and $x$=0.12 [3]. Following the same approach, we obtained the stripe localization temperatures $T_{ch}$ in our samples by crossing the normalized resistivities with appropriate thresholds extrapolated from the data of Ref. 3. Solid circles on curves a and b of Fig. 2 show the results of this operation. The inset of Fig. 2 shows the temperatures $T_{ch}$ of our crystals versus the Sr-doping (solid squares): they are in excellent agreement with $T_{ch}$ values determined by means of NQR measurement in LSCO crystals with different doping [2] (open squares). A further decrease of the temperature below $T_{ch}$ produces a continuous slowing-down of the stripe motion: stripes start to be pinned (by defects or by intrinsic low doping) and $\rho_{ab}(T)$ shows an upturn up to a peak followed by the region dominated by superconducting fluctuations.

One could argue that the small peaks at $T_o$ about 2 K above $T_c$ (see the inset of Fig. 2) may be due to measurement errors, $\rho_c$ interferences in $\rho_{ab}$, or crystal inhomogeneities (i.e. parts of the crystal are not superconducting and contribute to $\rho_{ab}$ with a semiconducting-like term just above $T_c$). We can reply to these objections that (i) the Van der Pauw’s four-probes AC technique provides four resistance measures and all of them show very reproducible peaks at $T_o$; (ii) a detailed data analysis suggests that the resistivity contribution of $c$-axis terms or different-doping islands is unable to give peaks as those observed [3]. Another possible explanation for their origin could be a structural low-temperature transition, similar to that observed at higher temperature in Nd-substituted samples [3], but there are no other evidences of such a transition near $T_c$ in LSCO.

We speculate that an electronic phase transition from a nematic stripe phase to a more ordered smectic one (“stripe glass”) [3] is responsible for the anomalies near $T_c$. This scenario is supported by theoretical arguments [3] and experimental analogies with the behaviour of some metal dichalcogenides at the charge-density wave transition and it is consistent with the coexistence of cluster spin-glass and superconductivity recently observed below $\sim$ 5 K in LSCO with $x = 0.06$ [3].

REFERENCES

1. J.M. Tranquada et al., Phys. Rev. B 54 (1996) 7489.
2. A.W. Hunt et al., Phys. Rev. Lett. 82 (1999) 4300; P.M. Singer et al., cond-mat/9906140.
3. N. Ichikawa et al., cond-mat/9910037; J.M. Tranquada et al., Phys. Rev. B 59 (1999) 14712.
4. S.A. Kivelson and V.J. Emery, cond-mat/9809082; S.A. Kivelson et al., Nature 393 (1998) 550.
5. R.S. Gonnelli et al., to be published.
6. M.-H. Julien et al., Phys. Rev. Lett. 83 (1999) 604.