Magnetic-Field Induced Superconductor-Insulator Transition in the $La_{2-x}Sr_xCuO_4$ System

K. Karpińska,[1] A. Malinowski,[1] Marta Z. Cieplak,[1,2] S. Guha,[2] S. Gershman,[2] G. Kotliar,[2] T. Skośkiewicz,[1] W. Plesiewicz,[1] M. Berkowski,[1] and P. Lindenfeld[2]

[1]*Institute of Physics, Polish Academy of Sciences, 02 668 Warsaw, Poland*

[2]*Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08855*

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The magnetoresistance of underdoped $La_{2-x}Sr_xCuO$ films with $x = 0.048$ and 0.051 is studied in magnetic fields up to 8.5 T and at temperatures down to 30 mK. The results indicate that the magnetic-field induced superconductor-insulator (SI) transition is qualitatively different from the reentrant transition described for indium oxide and interpreted as leading to a "bosonic insulator" phase. The ground state in the absence of superconductivity appears to be insulating. The transitions become narrower below 1 K and show that the resistive critical field diverges approaching zero temperature, as has also been observed in other high-T_c systems. [S0031-9007(96)01344-0]

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We report measurements of $La_{2-x}Sr_xCuO_4$ (LSCO) with values of x of 0.048 and 0.051, superconducting but strongly underdoped, and very close to the metal-insulator (MI) transition. The observations show an upper-critical-field anomaly, i.e., an increase of the resistive upper critical field as T goes toward zero, down to the lowest temperature of our experiment. A similar variation has been reported in other, quite different high-T_c materials [1–3]. The experiment also shows that the suppression of superconductivity by the magnetic field leads to the insulating state, without, however, any sign of reentrant behavior, or of a critical field at which the resistance becomes temperature independent, as observed in indium oxide [4] and attributed to the transition to a "bosonic-insulator" phase [5].

Other studies of field-induced superconductor-insulator (SI) transitions have been made primarily for strongly disordered systems [4,6–8] in contrast to those reported here, which are on highly ordered quasi-single-crystal films. There were two previous reports of field-induced SI transitions in perovskite systems, on strongly deoxygenated $YBa_2Cu_3O_{7-x}$ [9] and on $Nd_{2-x}Ce_xCuO_4$ [10]. However, only one specimen was measured in the first case, and the measurements were restricted to the region above 1.7 K in the second. These experiments were interpreted as leading to the bosonic-insulator phase. In this respect our results are different, indicating that the transition leads to the normal (fermionic) insulating phase.

One of the obstacles to measurements of the critical field in high-T_c superconductors is that the high transition temperature is accompanied by a very high critical field, up to the megagauss range. In addition, a broadening of the transition is generally observed in a magnetic field. In the present specimens the close proximity to the MI transition causes T_c to be strongly reduced, and as a result the upper critical field becomes accessible in relatively small fields. Furthermore, the transitions in our specimen with $x = 0.051$ are quite sharp, and become even sharper as the temperature is lowered below 1 K.

The LSCO specimens were grown from ceramic targets by pulsed-laser deposition. They are c-axis oriented, with thicknesses between 5000 and 9000 Å, deposited on substrates of crystalline $SrLaAlO_4$, which is isostructural with LSCO, with a lattice mismatch of 0.5% between substrate and film [11]. The samples were patterned by photolithography, and silver contacts were then evaporated. The zero-resistance superconducting transition temperature T_c and the zero-field resistivity ρ_{ab} measured at 40 K are shown in the inset of Fig. 1 for films with various values of x. It may be seen that T_c drops to zero and the resistivity increases dramatically near $x = 0.05$, i.e., at the MI transition. The values of T_c near optimal doping are lower than for bulk

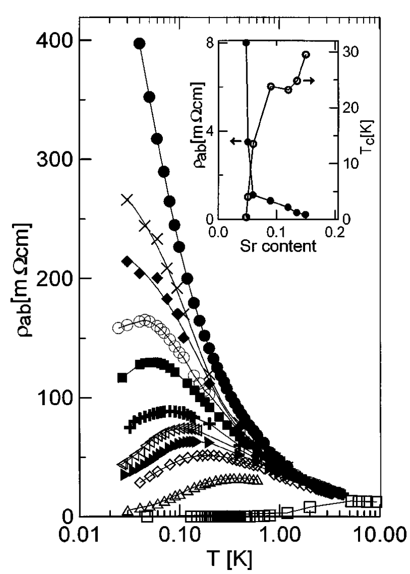

FIG. 1. The temperature dependence of ρ_{ab} of sample F1 with $x = 0.048$, with the field perpendicular to the a-b plane. The fields are, from below, 0, 1.7, 2.0, 2.2, 2.3, 2.4, 2.6, 2.7, 2.8, 2.9, and 3.0 T. The inset shows T_c, and ρ_{ab} at 40 K and zero field, for LSCO films with various values of x. The lines are guides to the eye.

samples because of the oxygen deficiency that we have previously described [12]. We describe measurements on two films, F1, with $x = 0.048$, $T_c = 450$ mK, and ρ_{ab} (at 40 K) = 8 mΩ cm, and F2, with $x = 0.051$, $T_c = 4$ K, and ρ_{ab} (at 40 K) = 3.5 mΩ cm.

Four-point low-frequency ac measurements were made with currents of the order of 1 nA, adjusted to maintain the Ohmic response of the specimens. The samples were mounted in a dilution refrigerator where they were cooled down to 30 mK. Magnetic fields up to 8.5 T were applied both perpendicular and parallel to the a-b plane. We discuss only the measurements in the perpendicular configuration, for which the magnetic field has a strong effect on the superconducting transition.

Logarithmic plots of the resistive transitions of the two films in the presence of magnetic fields are shown in Figs. 1 and 2. Small magnetic fields cause a broadening of the transition and decrease the zero-resistance temperatures. As the magnetic field increases, a pronounced maximum appears, and shifts to lower temperatures with increasing field. For sample F1 the maximum moves below the lowest measurable temperature at a field of 2.8 T. At higher fields the resistivity shows no signs of superconductivity and increases steeply as the temperature is lowered, suggesting that the field induces a superconductor-insulator transition. For sample F2 the maximum field that we apply is too weak to suppress superconductivity completely. However, the field causes qualitatively similar changes in the resistance, with a more pronounced maximum and a relatively sharp drop of the resistance on the low-T side of the maximum. We note that none of the superconducting transitions shown in Figs. 1 and 2 shows any sign of the reentrant behavior first observed in indium oxide [4]. Moreover, down to the lowest temperature of our measurements, $T = 30$ mK, we do not observe a critical field at which $\rho(T)$ becomes independent of T, although this possibility cannot be completely ruled out at still lower T.

Figure 3 shows the temperature dependence of ρ_{ab} plotted as $\log \rho_{ab}$ against $T^{-1/4}$ for film F1. The figure shows that the data follow straight lines from 4 to 6 T, indicative of Mott hopping. (The data are also consistent with the exponent $\frac{1}{3}$ which would be expected in a 2D system.) We conclude that the straight lines on this graph reflect the true insulating character of the normal state of this specimen. The deviations at lower fields may be attributed to superconducting fluctuations. If we assume that these fluctuations are suppressed at fields of 4 T and higher, then the figure shows that the magnetoresistance is positive.

It may be seen in the inset to Fig. 3 that this same specimen that shows hopping behavior at low temperatures exhibits a linear dependence of ρ_{ab} on T above 200 K.

The temperature dependence of the normal state of film F2 (Fig. 2) is more difficult to assess because superconductivity is not completely suppressed at any field. The two curves at the highest fields, 8 and 8.5 T, are quite close to each other to the right of the maximum, indicating that they are in or close to the normal state. At these fields the T dependence is somewhat faster than logarithmic down to about 700 mK, leading us to conclude that in the absence of superconductivity the ground state is insulating in this specimen also. A logarithmic dependence down to low temperatures would be quite unusual, although the theory of weak localization in 2D systems predicts a logarithmic temperature dependence of the conductivity [13]. Our result may be compared to that

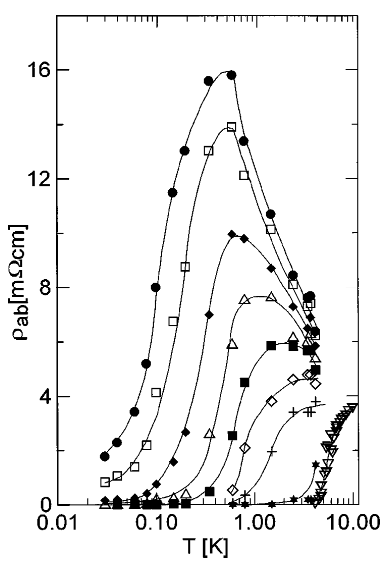

FIG. 2. The temperature dependence of ρ_{ab} for sample F2, with $x = 0.051$, in perpendicular fields. The fields are, from below, 0, 1, 3, 4, 5, 6, 7, 8, 8.5 T. The lines are guides to the eye.

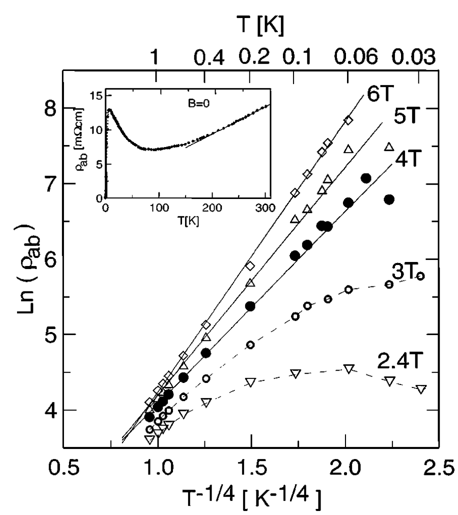

FIG. 3. Log ρ_{ab} as a function of $T^{-1/4}$ for film F1 in fields of 2.4, 3, 4, 5, and 6 T. The straight lines are fits to the points, the broken lines are guides to the eye. The inset shows ρ_{ab} as a function of T up to 300 K for the same film.

of Ando *et al.*, who measured the resistance of single crystals of LSCO with $x = 0.08$ and $x = 0.13$ at temperatures down to 0.7 K and fields up to 60 T [14], and concluded that the resistivity is proportional to $\ln(1/T)$, in both the *a*-*b* plane and along the *c* axis, so that a theory that applies only to 2D systems would seem not to be applicable. The fact that the observed dependence of R on T is faster than logarithmic suggests that it represents a crossover region to a low-temperature hopping regime as in specimen F1. We note that the hopping behavior of film F1 is observed at temperatures well below 1 K. This low-temperature insulating regime was not accessible using available fields in film F2, nor in the measurements conducted by Ando *et al.*

We also note that there is a distinct difference in the behavior of these two specimens from that previously observed in LSCO with impurities substituted at the copper site [15]. In that case the conductivity extrapolates to a finite value as T goes to zero, indicating the existence of a metallic nonsuperconducting phase. Our present results show that no such phase seems to exist when the carrier concentration is changed by altering the La-Sr ratio rather than by substitutions in the copper-oxide plane.

We now turn our attention to the temperature dependence of the upper critical field, $H_{c2}(T)$. Figure 2 shows a sharpening of the superconducting transitions as the temperature is lowered below 1 K. This effect was not observed in previous studies of the LSCO system, which were made at higher temperatures [16] so that we tentatively associate the sharpening with the presence of low temperatures rather than high magnetic fields. This may be because the broadening of the superconducting transition in magnetic fields is caused by flux-flow effects, which are reduced or eliminated at the lowest temperatures. The narrowing allows us to attempt to determine the dependence of H_{c2} on T from the resistance data. As an approximation to the true critical field we choose the field H^* at which the resistivity is 10% below its maximum value. Figure 4 shows H^* as defined in this way as a function of temperature. To assess the influence of the width of the transition on $H^*(T)$ we also show the fields at which the resistivity is 20% and 50% below the maximum. Below 1 K, where the transitions are sharper, the scatter is quite small, and the 10%, 20%, and 50% points are close to each other. We see the upward curvature of $H^*(T)$ down to our lowest temperature of about $0.007T_c$, similar to that previously observed in two overdoped, and one underdoped high-T_c systems [1–3].

The observation of a similar variation of the critical field in the underdoped and overdoped systems does not necessarily mean that the origin of this effect is the same on both sides of the phase diagram. In the case of the heavily underdoped specimens that we investigate there is the possibility that the carriers are influenced by magnetic ordering at low temperatures. Such coupling is known to result in unconventional behavior of H_{c2} in some ternary rare-earth compounds [17]. On the other hand, it is also possible that the origin of the anomaly is the same as in the overdoped compounds. Several theoretical interpretations have been proposed. Alexandrov *et al.* considered the Bose condensation of bipolarons partly localized in a random potential [18]. Our attempt to fit the formula for $H_{c2}(T)$ predicted by this theory to the experimental data leads to the rather high value of 300 Å for the zero-temperature coherence length ξ_0, and to the value of 21 K for T_c, which is much higher than the observed value. There are several other theoretical models in which $H^*(T)$ is identified with $H_{c2}(T)$, including the models which link the upward curvature of H_{c2} to a temperature-dependent effective mass [19], to the properties of the normal state [20], or to strong fluctuation effects [21]. Most of these theories are capable of reproducing the upward curvature of $H_{c2}(T)$, but the fits to the experimental data are usually limited to a narrow temperature region.

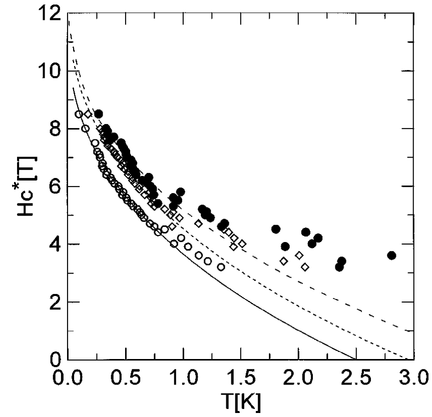

FIG. 4. The resistive critical field H^* versus temperature for sample F2. The values of H^* were chosen at the points where the resistivity is 10% (•), 20% (◇), and 50% (∘) below the resistivity maximum. The curves are the melting lines as calculated from Ref. [23], with $H_c(0)$ and T^* parameters for the three curves, from below, 11.9 T and 2.7 K, 12.9 T and 2.95 K, 12.95 T and 3.6 K.

There are also theories which link the anomaly of the observed $H^*(T)$ curve with the melting of the vortex lattice, either in two dimensions [22] or in three dimensions [23]. The broadening of the superconducting transition which we observe at temperatures above 1 K suggests that vortex motion may indeed influence the behavior of the resistive transition. We therefore compare our experimental results with the model of Kotliar and Varma [23] who identify H^* with the melting line of the Abrikosov lattice, and propose to explain the anomaly by the existence of a zero-temperature quantum critical point. According to this model the melting line is described by $H_m(T)/H_{c2}(0) = 1 - (T/T^*)^{2/5}$, where H_m is the field at the melting line, and the characteristic temperature T^* is related to the Ginzburg parameter κ and to the masses in the Landau-Ginzburg Hamiltonian M and M_z by the relation $T^* \approx 0.44 \times 10^8 \alpha/\kappa^2 (M_z/M)^{1/2}$. Here α is a dimensionless constant expected to be less than one. The lines in Fig. 4 show fits that we obtain to the three sets of data for the points 10%, 20%, and 50% below the maximum, with values of the two fitting parameters, T^* and $H_{c2}(0)$, equal to 3.6 K and 12.95 T for 10%, 2.95 K and 12.9 T for 20%, and 2.7 K and 11.9 T for 50%. The formula is seen to describe the data very well below 1 K. The origin of the deviation above 1 K may be that the experimental points are outside the critical region, or because of the broadening of the transition.

If H^* is identified as the field at the melting point of the vortex lattice, it is probably better represented by the midpoint of the transition curve. Indeed, the 50% experimental points give the best fit. The fields for 10% and 20% will then be at temperatures that are too high, in keeping with their observed deviation. H_{c2}, on the other hand, must be expected to be at values of T near or even above the maximum on Figs. 1 and 2.

The observation of a continuous increase of the upper critical field, apparently without saturation, indicates that this may be a feature characteristic of perovskite superconductors. In addition, our experiment shows that the magnetic transition in the specimen with $x = 0.048$ is from the superconducting state to an insulating state characterized by variable-range hopping, and that this may also be the case in the specimen with $x = 0.051$. Finally, we see no evidence for a bosonic-insulator phase, or for a metallic nonsuperconducting phase.

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