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Pressure studies on the pseudogap and critical temperatures of a high-T_c superconductor

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We report simultaneous hydrostatic pressure studies on the critical temperature T_c and on the pseudogap temperature T^* performed through resistivity measurements on an optimally doped high-T_c oxide $Hg_{0.82}Re_{0.18}Ba_2Ca_2Cu_3O_{8+\delta}$. The resistivity is measured as a function of the temperature for several different applied pressures around 1 GPa. We find that T^* increases linearly with the pressure at a larger rate than T_c. This result demonstrates that the well known intrinsic pressure effect on T_c is more important at the pair formation temperature T^*.

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I. INTRODUCTION

Immediately after the discovery of the high-T_c superconductors[1] high pressure experiments have played an important role in improving and understanding these materials. However, despite of tremendous efforts, the superconducting interaction in high-T_c oxides[1] remains one of the greatest puzzle in condensed matter physics. More recently, several experiments[2] indicate that the appearance of a pseudogap, that is, a discrete structure of the energy spectrum at a temperature T^* above the superconducting phase transition temperature at T_c is an important property which needs to be taken into account in the quest for the solution of this problem.[3] However, one difficulty is that different techniques, depending on the particular experimental probe used, may yield different values of pseudogap temperature T^* for the same type of sample.

There are mounting evidences that the pseudogap and the charge inhomogeneities, possibly in a stripe morphology,[4,5] are different but closely related phenomena. This is mainly because T^* has its maximum value for underdoped compounds[2] which possess the larger charge inhomogeneities.[6,7] Furthermore T^* decreases with the average doping level and probably becomes equal to T_c for overdoped compounds which are those with more homogeneous charge distributions.[8,9] Moreover, a local Meissner state, which usually appears only in the superconducting phase, has been detected far above T_c for an underdoped sample.[10] Such inhomogeneous diamagnetic domains develop near[11] T^* for $La_{2-x}Sr_xCuO_4$ thin films and grow continuously as the temperature decreases towards T_c. Near T_c, the domains appear to percolate through the sample.

Based on these experimental findings, some of us have developed a new approach to deal with this phenomenology.[3] The main ideas are the following; compounds of a given family, with an average charge density ρ_m have inhomogeneous charge distributions which are less homogeneous for underdoped and more homogeneous for overdoped samples. These distributions contain a hole-rich and a hole-poor partition which mimics the stripes. These charge inhomogeneities in the hole-rich regions produce local clusters with spatially dependent superconducting gaps $\Delta_{sc}(r)$ due to local Cooper pairing and superconducting temperatures $T_c(r)$. T^* is the largest of all the $T_c(r)$, that is, the largest local superconducting temperature in a given compound. Since the clusters have different charge densities, some are metallic and some are insulating. As the temperature decreases below the T^*, part of the metallic clusters become superconducting and, eventually, a temperature is reached where the different superconducting clusters can percolate, exactly as clearly demonstrated by the fine diamagnetic domains measured by Iguchi *et al.*[10] At or below the percolation temperature, the system can hold a dissipationless supercurrent and this temperature is normally identified as superconducting critical temperature T_c. Thus, the temperature T_c is assumed to be the percolating transition for the supercurrent and it is not the usual superconducting transition related with the appearance of a superconducting gap. This scenario resembles the proposal of Ovchinnikov *et al.*[12] and its implications are discussed in Ref. 3.

According to these ideas, experiments which produce changes on T^* are able to provide direct information on the superconducting interaction. One such type of experiment is the isotopic substitution of ^{16}O by ^{18}O in the slightly underdoped $HoBa_2Cu_4O_8$ which leads to an increase in T^* from 170 to 220 K and negligible effect on T_c.[13] Despite the anomalous increase of T^* for the heavier isotope, this result indicates that, at least for this sample, electron-phonon induced effects are likely to be present in the mechanism related to T^* and somehow, are less important on T_c.

The prime objective of this work is to study the nature of the pseudogap and to achieve this goal we analyze resistivity measurements under low applied hydrostatic pressures. The measurements were performed on two different optimally doped $Hg_{0.82}Re_{0.18}Ba_2Ca_2Cu_3O_{8+\delta}$ samples in temperatures range from 120 K (below T_c) up to room temperatures. The resistivity for underdoped and optimally doped high-T_c oxides has a linear behavior up to very high temperatures but at T^*, it downturns and falls faster as temperature is decreasing.[2] We have recently reported pressure effects on T_c on this compound,[14,15] but our aim here is to study simultaneous pressure effects on T^* and T_c. We show that T^* increases at larger rate than T_c in the pressure range of our experiment. This result provides a novel interpretation for the well known pressure intrinsic effect.

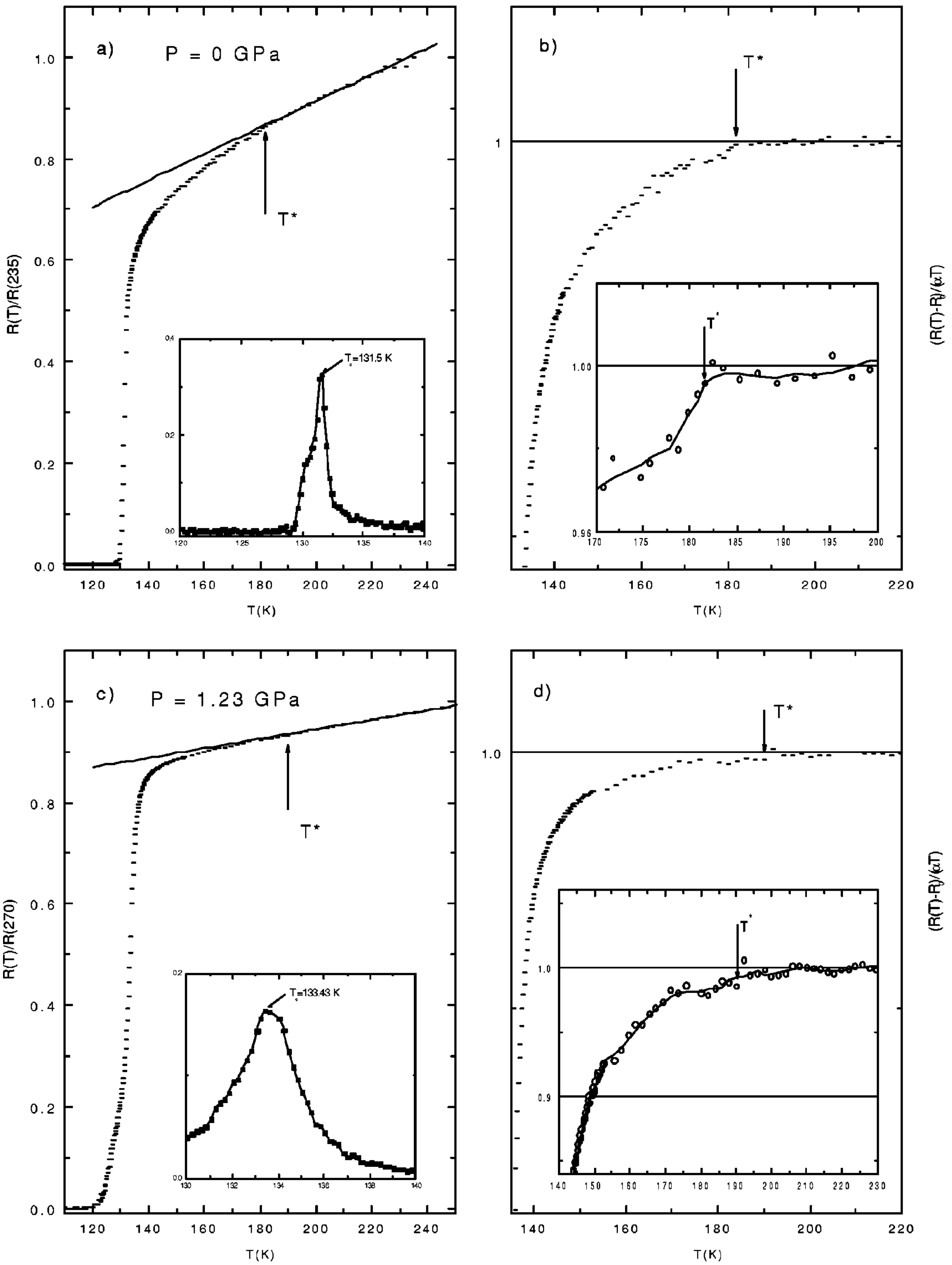

FIG. 1. The resistivity measurements for sample A as a function of the temperature for zero and 12.3 Kbar. The criterion for T_c (where dR/dT has the largest value) is shown in the inset of panels (a) and (c). The criterion for T^* is shown in panels (b) and (d) and in their inserts.

II. EXPERIMENTAL MEASUREMENTS

The resistivity measurement were performed using an hydrostatic pressure cell within a cooper cylinder piston. An external pressure was applied to the cylinder and it was transmitted through a n-pentane-isoamyl alcohol mixture (1:1) to the sample. The sample was mounted on a Teflon sample holder, and in order to provide a good thermal contact with the temperature sensor, the sample holder was thermally coupled to the CuBe pressure cell. The pressure was monitored with a manganin resistance situated inside the cell. Further details of this experimental set-up can be found elsewhere.[14–17]

Four electric contacts with low electric resistance were deposited onto the sample by using silver paint. After stabilizing the pressure, the temperature was increased recording the resistance on the sample. This procedure was repeated at several pressures leading to the $R(T,P)$ curves. The temperature was recorded and stabilized using a "Lake-Shore-340" temperature controller. The resistance measurements were performed using an ac-bridge resistance "Linear Research Inc, model LR-700." The $R(T,P)$ curves were measured within the linear-response regime with an applied current to the sample of 10 μA.

III. RESULTS AND DISCUSSION

We have measured the resistivity for two optimally doped $Hg_{0.82}Re_{0.18}Ba_2Ca_2Cu_3O_{8+\delta}$ samples (A and B) as a function of temperature for four different applied pressures up to the 1.23 GPa. The samples were made under the same conditions. As an example of our results, the temperature dependent resistivity data for sample A at zero pressure and 1.23 GPa are shown in Fig. 1.

Panel 1(a) shows the data for $R(T)$ and 1(b) shows a plot of $[R(T)-R_0]/\alpha T$ against T, where R_0 and α are respectively, the intercept and the linear coefficient of the high temperature linear part of the $R(T)$ curve. The T^* temperature was taken at the point where the experimental resistance curve starts to downturn from the high-temperature linear behavior. To determine T^*, we have used the same criterion of Ito *et al.*[18] which is shown in Fig. 1(b). At each applied pressure, T^* was taken as the temperature at which the curve starts to downturns from its base-value as demonstrated in panels 1(b) and 1(d). It should be noted that others criteria for T^* leaded to practically the same experimental findings, meaning that the T^* increase with the pressure is independent of its experimental criterion.

The critical temperature T_c was defined as the temperature for which the dR/dT has the largest value[19] as shown in panels 1(a) and 1(c). We have measured an experimental dT_c/dP rate of 1.5 K/GPa for sample A and 2.6K/GPa for sample B, which are typical values for these multilayer compounds.[15] In order to verify these derivatives we have performed magnetic susceptibility measurements on both samples. The increase of T_c with the applied pressure is in the range of similar compounds which we have previously been reported.[14,15] While sample A has $T_c \approx 131.5$ K and $T^* \approx 180$ K at ambient pressure, sample B has $T_c \approx 132.0$ K and T^* just above 160 K. Since both the present samples and the ones previously studied were made under the same condition, we do not have an explanation for these differences. Nevertheless it is a common fact that different samples of the same compound with the same T_c, may exhibit large differences in their T^* value.[2]

The theory of pressure effects[20,21] identify two contributions to the changes on T_c: a pressure induced charge transfer (PICT) from the charge reservoirs to the CuO_2 planes and an intrinsic term, of unknown origin, which is more clearly detected mainly at, or near to, the optimally doped compounds. In the case of optimal doping and low pressure, i.e., less than 5 GPa, there is a negligible PICT (Refs. 14, 21) and T_c is a linear function of the pressure. This linear behavior is therefore attributed entirely to the intrinsic contribution[20,21] and it is believed to be due to the effect of the pressure on the superconducting interaction.[22–24] It can be regarded as due to an intrinsic increase on the superconducting interaction, which makes the Cooper pairs more tightly bound and also increases the superconducting gap.

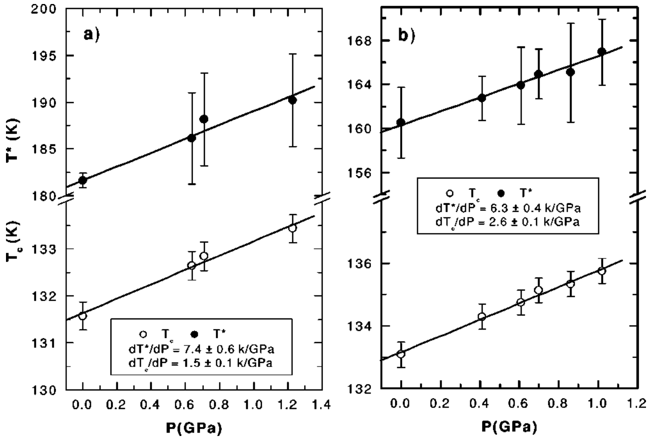

FIG. 2. The estimated values for T_c and T^* as function of the applied pressure for both samples. Data in panel (a) is for sample A and (b) for sample B. Notice that both samples have linear variations pressure variations for T_c and T^*. The error bars are visually estimated from the insets in Figs. 1(b) and 1(d).

Thus, in order to determine whether the pseudogap is also affected by an external pressure and if the intrinsic effect is also present at the pseudogap temperatures, we plotted in Figs. 2(a) and 2(b) the T_c and T^* values obtained from the resistivity data. While sample A has $T^* \approx 180$ K at ambient pressure, sample B hat $T^* \approx 160$ K. Through these figures we can see the original and most important result of our work: T^* and T_c increase under the applied pressure in a linear way, but dT^*/dP is around 3–5 times larger than dT_c/dP. For sample A we get $dT^*/dP = 7.5$ K/GPa and $dT^*/dP = 6.3$ K/GPa for sample B. This behavior lead us to the main conclusion of this work, namely, the pressure induced intrinsic term modifying T_c is much stronger on the pairing formation temperature T^*.

Our experiment reveals a larger pressure effect on T^* than on T_c. We have already mentioned the results of Temprano *et al.*[13] with different isotope effect on these temperatures. Similarly Harris *et al.*[25] have demonstrated with ARPES measurements that the zero temperature superconducting gap Δ_{sc} does not correlates with T_c. However, according to the percolation scenario for high-T_c oxides,[3] Δ_{sc} correlates with the onset of superconducting gap T^* and not with T_c (see Fig. 3 of Ref. 3).

We have mentioned that our most important finding is the larger linear increase on T^* than on T_c and such behavior is possibly the consequence of the intrinsic pressure effect on the superconducting interaction.[22,23] The presence of a constant intrinsic term on both T_c and T^* is an indirect evidence of the increase of the superconducting interaction. However, we will argue that this result could either be explained under the assumption of a phonon mediated mechanism or by a non-equivalent two layer hole density. In a typical BCS superconductor, either in weak[26] or strong[27] coupling regime, T_c is proportional to the Debye frequency $\hbar\omega_D$ and to $\exp[-1/N(0)V]$, where $N(0)$ is the density of state and V the phonon mediated pairing potential amplitude. These two terms yield opposite contributions when the sample is under an external applied pressure. The applied pressure increases ω_D in any solid and also broaden the density of states, thereby reducing $N(0)$ which is the dominant factor in a typical BCS superconductor and produces an overall decrease in T_c. Now, assuming the same type of dependence on high-T_c superconductors, the effect on $N(0)$ is minimized in a high-T_c sample with a large charge inhomogeneities distribution because such inhomogeneities produce also a broadening of the density of states, as clearly demonstrated by Ovchinnikov *et al.*[12] Therefore the net low pressure effect on an optimally doped cuprate is to increase ω_D which yields a proportional linear increase on all $T_c(r)$ in the sample and, consequently, on T^*, assuming, according Ref. 3, that T^* is the pair formation temperature. Since at the low pressures all values of $T_c(r)$ throughout the sample increase proportionally to ω_D, the percolation temperature T_c will also increase. This reasoning provides a physical interpretation to the linear behavior of both T^* and T_c and to the well known pressure intrinsic effect which, despite of being widely detected,[20–24] has not received any previous microscopic interpretation.

Another interesting possibility to explain the increase of T_c and T^* under pressure uses the idea of a competition between two hole dependent effects:[29] Pairing formation which decreases with doping and the system stiffness to phase fluctuations which controls long-range phase coherence and increases with doping. On the other hand, it is well known that three layer compounds, such as our $Hg_{0.82}Re_{0.18}Ba_2Ca_2Cu_3O_{8+\delta}$ samples A and B, must have differences in the doped hole concentration in the different layers.[19,21] Therefore one layer may have a hole concentration which favors pairing and the other may favor phase coherence. The pressure induced charge transfer (PICT) between different layers may lead to an optimal dependent distribution of doped holes which increases the layer superfluid stiffness, producing an enhancement in T_c, concomitantly with an increase in the pairing scale, and therefore an enhancement in T^*.[29]

IV. CONCLUSION

We have reported here simultaneous hydrostatic pressure effects on the pseudogap temperature T^* and on T_c of an optimally doped high-T_c superconductor. We have measured a larger linear increase on T^* than on T_c under applied pressures up to 1.23 GPa. These data show that the intrinsic effect on T_c could be a consequence of the larger effect on the pair formation temperature T^*.

There are several implications from the pressure induced increase of T^* and T_c. The increase on T^* indicates the presence of the superconducting mechanism what supports the local Cooper pairing scenario due to the charge inhomogeneities in the CuO_2 planes.

Moreover, the linear behavior of T^* and T_c under pressure may be consistent with a mechanism leading to the formation of superconductivity mediated by phonons. This is in agreement with the very large isotope effect measured on T^* by Temprano *et al.*[13] and very recent ARPES measurements.[28] However the enhancement of T^* and T_c may also be due to the PICT between nonequivalent layers of our sample.[29]

We are presently pursuing our resistivity under pressure experiment with samples having different oxygen content. We believe that for underdoped compounds, T^* and T_c will behave in similar way as reported above. For more homogeneous overdoped samples we expect the broadening of $N(0)$ under applied pressure to be much less important and therefore T^* and T_c may not increase.

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