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THE STRANGE INTERPLANE CONDUCTIVITY OF HTSC

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Abstract—We review recent results on the anomalous c-axis optical conductivity of several high temperature superconductors, both double layer and single layer materials. We find that the double layer materials are characterized by a narrow pseudogap in the normal state that is also responsible for the temperature dependence of the transport. In the single layer material the pseudogap is much broader and less well defined. In the superconducting state, in both double and single layer materials, there is a transfer of spectral weight from very high frequencies to the condensate delta function at zero frequency.

1. INTRODUCTION

The interplane conductivity of the high temperature superconductors is peculiar [1]. The fully doped materials exhibit a metallic temperature dependence but with a high residual resistivity which does not result from impurity scattering, since samples from the same source show no sign of defect scattering when the resistivity is measured in the ab-plane [2,3]. Furthermore the frequency dependence of the conductivity of the fully doped samples is Drude-like with a very high scattering rate, high enough to correspond to a mean free path of less than a lattice spacing [4]. This lack of coherent conductivity can be understood in terms of the magnetism of the copper oxygen planes. There is no cell-to-cell coherence in the c- direction [5] and to transfer a hole from one unit cell to another, in that direction, it is necessary to rearrange the local magnetic structure. Thus each cell looks like a defect.

In this brief review we describe the results of recent work on the c-axis conductivity of some two-layer materials, underdoped $YBa_2Cu_3O_{6.70}$ [6,8] and $YBa_2Cu_4O_8$ [7] the double chain material that is naturally underdoped. We also show recent results on $La_{2-x}Sr_xCuO_4$ [9], a single layer material, also slightly underdoped.

2. EXPERIMENTAL RESULTS

Figure 1 shows the optical conductivity in the c-direction of an underdoped $YBa_2Cu_3O_{6.70}$. A series of strong phonon lines dominate the spectrum. As the temperature is lowered there is reduction in the conductivity at low frequency but the high frequency conductivity is temperature independent. The phonon structure in the oxygen mode region undergoes major changes as a function of temperature. There is a transfer of spectral weight from the bridging oxygen modes a

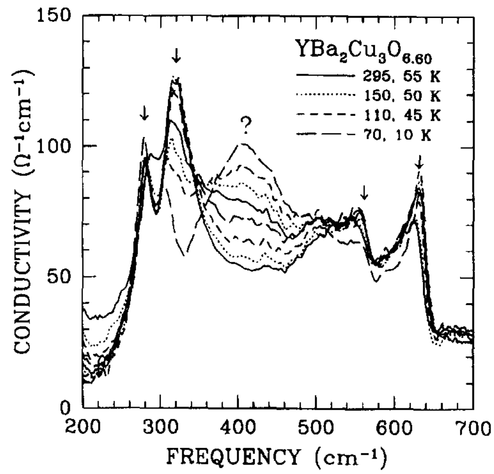

Fig. 1. The temperature dependence of the c-axis optical conductivity of $YBa_2Cu_3O_{6.6}$. The superconducting transition is at 58 K. A massive rearrangement of spectral weight occurs as the temperature is lowered: a feature at ≈ 400 cm^{-1} grows, and the correspondingly there is a loss of spectral weight of all the sharp phonon bands marked with arrows except the lowest one corresponding to chain buckling modes — there is no anomalous behavior near T_c.

570 and 610 cm^{-1} to a broad band centered at 400 cm^{-1}. The plane buckling mode at 310 cm^{-1} also loses spectral weight but the chain mode at 285 cm^{-1} is temperature independent.

In Fig. 2 the phonons and the broad line at 400 cm^{-1} have been removed from the spectrum. The resulting spectrum is dominated by a gap-like feature in the 200–300 cm^{-1} range. The feature deepens as the temperature is lowered towards 70 K, just above T_c. The bottom of this pseudogap is flat and the conductivity extrapolated to zero frequency (plotted in the inset) is in excellent agreement with d.c. transport measurements [10]. It is clear that the so-called semiconducting behavior of the c-axis resistivity in the underdoped materials is due to this pseudogap and that the conductiv-

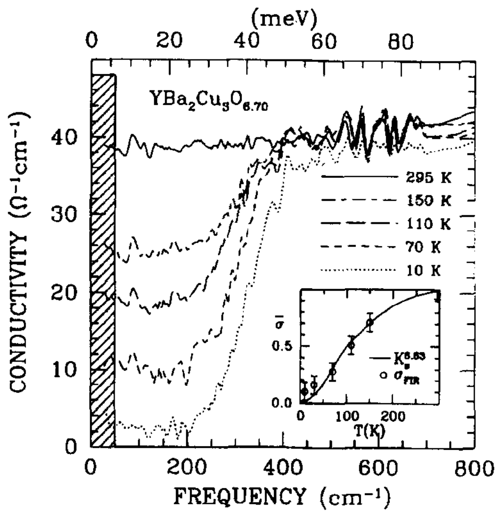

Fig. 2. The optical conductivity of $YBa_2Cu_3O_{6.70}$ (T_c=63 K) along the c-axis at 295, 150, 110, 70 and 10 K. Five strong phonons, and a feature at $\approx$ 400 cm^{-1} (believed to be due to phonons) have been removed. A gaplike feature develops in the conductivity near room temperature deepening as the temperature is lowered. In the superconducting state a further depression of conductivity takes place but over a much larger frequency range. The shaded rectangle shows the spectral weight under the superconducting condensate. Inset: The low frequency optical conductivity, normalized at room temperature, as a function of temperature shown as circles with error bars. The normalized NMR Knight shift is also shown.

ity at high frequency, above 400 cm^{-1}, is temperature and frequency independent. The spectral weight missing from the pseudogap region must go to much higher frequencies, outside of our range of accurate measurements.

By evaluating the imaginary part of the conductivity it is possible to calculate the area under the superconducting delta function peak, shown as the dashed box in Fig. 1. It can be seen that this area corresponds approximately to the area missing between the 70 K curve and the 10 K curve, but this area extends beyond the normal state pseudogap.

Figure 3, lower panel, shows frequency dependent c-axis conductivity for the double chain material $YBa_2Cu_4O_8$ [7]. The normal state conductivity for this material is of the same order of magnitude as the fully doped $YBa_2Cu_3O_{6.95}$ [6] and the frequency dependence has a Drude-like component with a scattering rate of approximately 400 cm^{-1}, superimposed on an incoherent background. Despite this, almost metallic, behaviour the material is underdoped and shows a clear pseudogap as the temperature is lowered. The 82 K curve shows the pseudogap clearly. In the superconducting state, at 10 K, the pseudogap has deepened but the most striking development is the high density superconducting condensate, shown as the shaded area at the bottom of the diagram. It is clear that the spectral weight for the condensate is coming from a frequency range of the order of 1000 cm^{-1}.

The top panel of Fig. 3 shows the c-axis conductivity of $La_{2-x}Sr_xCuO_4$ [9]. Here the overall room temperature conductivity is lower and the temperature dependence is

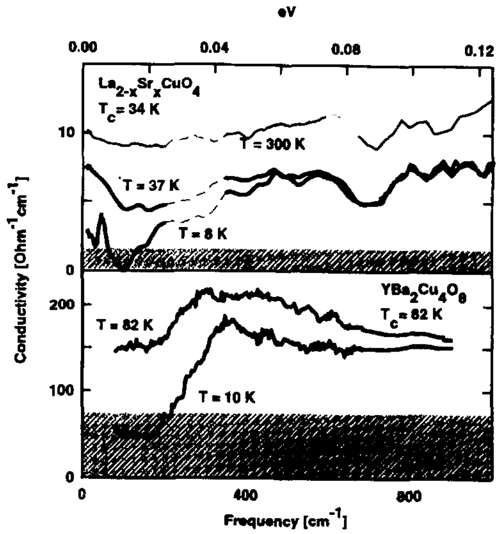

Fig. 3. The *c*-axis conductivity of the single-layered $La_{2-x}Sr_xCuO_4$ (top panel) and of the double-layered $YBa_2Cu_4O_8$ (bottom panel) at different temperatures. Phonon peaks have been subtracted foı clarity. The dashed fragments of the spectra in the top panel show the frequency range where the subtraction of phonons has considerable uncertainty. Dashed areas in both panels correspond to area under the superconducting condensate determined from the imaginary part of the conductivity.

quite different from the two-layer materials. There is approximately a factor of two reduction in the conductivity to low temperatures but the pseudogap, if present, is an order of magnitude larger than in the two layer materials. We have been able to isolate the destination of the spectral weight by careful measurements on very large samples. We find that the conductivity is reduced up to 5000 cm^{-1} but increased between 5000 cm^{-1} and 8000 cm^{-1} (1 eV) and the sum rule is obeyed, at all temperatures, if the conductivity is integrated up to 1 eV.

In $La_{2-x}Sr_xCuO_4$, too there is a further reduction in the conductivity when the superconductivity develops and again the spectral weight of the condensate, shown as the gray area in the top panes of the figure, comes from a much larger region than $3.5kT_c$ = 83 cm^{-1}.

3. DISCUSSION

The pseudogap observed in the underdoped two-layer cuprates has several unusual properties. First, the missing spectral weight does not reappear near the gap frequency as it does in the case of an spin density wave gap [13] or as a low frequency collective mode as seen in the superconducting transition. The second unusual effect is the lack of temperature dependence of the gap frequency. This gap with a value of only 2Δ = 200 K persists to nearly room temperature with out closing up or broadening much. Most importantly, it is a *pseudogap* in the sense that even at lowest temperatures there is no region of zero conductivity, the conductivity remaining finite at all frequencies and temperatures.

The relationship between superconductivity and the pseudogap is subtle. It seems, more from the higher resolution Knight shift measurements [11] than the optical conductivity, that the depth of the pseudogap, has an inflection point at the superconducting T_c as if the pseudogap ceased to develop below this temperature [12]. It seems that the process of transfer of spectral weight is arrested at T_c.

Another possibility is that the pseudogap is associated with lattice vibrations in some way. Thus for example, in parallel with the gap in the electronic conductivity, much of the spectral weight of oxygen phonons corresponding to plane buckling and apical c-axis motion is shifted to a new broad mode at 400 cm^{-1} [14].

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