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$_2$Cu$_3$O$_{6.7}$ [6,8] and YBa$_2$Cu$_4$O$_8$ [7] the double chain material that is naturally underdoped. We also show recent results on La$_{2-x}$Sr$_x$CuO$_4$ [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$_2$Cu$_3$O$_{6.7}$. 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 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$_2$Cu$_3$O$_{6.70}$ ($T_c=63$ 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.

Fig. 3. The c-axis conductivity of the single-layered La$_{2-x}$Sr$_x$CuO$_4$ (top panel) and of the double-layered YBa$_2$Cu$_3$O$_6$ (bottom panel) at different temperatures. Phonon peaks have been subtracted for 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.

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 $2\Delta = 200$ 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 temper-
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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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REFERENCES

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