Temperature dependence of the resistivity of oxygen controlled Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ thin films: pseudogap effect

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Abstract

We have investigated the temperature dependence of the resistivity $\rho_{\alpha\beta}(T)$ of epitaxial $c$-axis oriented Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ thin films, at different oxygen content. A film is brought, by successive annealing treatments, from maximally overdoped ($T_c = 62$ K) to strongly underdoped ($T_c < 4.2$ K) still metallic states ($d\rho/dT > 0$). When decreasing $T$, $\rho_{\alpha\beta}(T)$ for overdoped states departs from linearity with an upward curvature whereas for optimally doped and underdoped states it drops from linearity with a downturn starting at a temperature $T^*$, which increases with decreasing $T_c$, i.e. decreasing carrier concentration. This characteristic temperature $T^*$ is in close agreement with the values reported in the literature from ARPES measurements on Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals, attributed to the opening of a pseudogap in the excitation spectrum. It is proposed that the faster decrease of $\rho_{\alpha\beta}(T)$ observed below $T^*$ has the same origin.

The pseudogap effect observed in underdoped high-$T_c$ superconductors has been the center of attention for the last few years as the most intriguing phenomenon of the normal state of cuprates and is critical for understanding their superconducting state [1,7—12]. More recently, observations by angle-resolved photoemission spectroscopy (ARPES) of underdoped Bi-2212 single crystal have shown an energy gap in the normal state excitation spectrum [2,3]. In this paper we present the signature of this effect in the temperature dependence of the resistance of Bi-2212 thin films examined in different doping states.

A series of $c$-axis oriented epitaxial Bi-2212 films, 2000 Å thick, were grown by RF magnetron sputtering [4]. The temperature dependence of the resistivity was measured at different oxygen doping levels, going from overdoped to underdoped states for a given film. The optimally doped state ($T_c(R = 0) = 77$—$80$ K) and the underdoped states are subsequently achieved by progressively removing oxygen through repeated vacuum annealing treatments. The change of the Hall coefficient at 300 K, measured in a magnetic field of 1 T, confirms that the described annealing procedure produces a change in oxygen content in the film. The temperature dependence of in-plane resistivity $\rho_{ab}$ was measured using standard four-probe method on mechanically patterned films, equipped with gold sputtered contact pads.

Fig. 1 shows a typical set of curves, representing $\rho_{ab}(T)$ as a function of temperature, obtained on the same film studied in one overdoped state ($T_c(R = 0) = 69$ K) and in a series of underdoped states with $T_c(R = 0)$ decreasing from 74 K to less than 4.2 K. There is no sign of insulating behaviour ($d\rho_{ab}/dT < 0$) for all superconducting underdoped states even for $T_c < 4.2$ K. The temperature dependence of $\rho_{ab}(T)$ displays a $T$-linear behaviour near the room temperature in all investigated states. As the temperature is reduced from this linear region, $\rho_{ab}(T)$ develops a positive curvature in the overdoped case and...
Fig. 1. The temperature dependence of the in-plane resistivity of a Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ thin film measured at various oxygen content. The arrows indicate the characteristic temperature $T^*$ at which the deviation from $T$-linear behaviour starts. The inset shows $[(\rho_{ab} - \rho_0)/\alpha T]$ as a function of temperature for overdoped and underdoped states with the same $T_c$ value equal to 69 K.

a negative one in the underdoped states. The latter behaviour corresponds to a faster decrease of $\rho_{ab}(T)$ occurring at a characteristic temperature $T^*$. A more precise way of studying these different behaviours is by replotting the data as $[(\rho_{ab}(T) - \rho_0)/\alpha T]$ against $T$, where $\rho_0$ and $\alpha$ are the parameters obtained from the linear fit of the high-temperature part of $\rho_{ab}(T)$. The results for the overdoped and the underdoped states with both $T_c(R = 0) = 69$ K are compared in the inset of Fig. 1. The overdoped state shows a deviation from linearity above the normalisation line. The underdoped state shows a downturn from the normalisation line which starts at a characteristic temperature $T^*$. The arrows in the main plot indicate the as-determined values of $T^*$ for $T_c \geq 40$ K. The characteristic temperature $T^*$ increases as $T_c$ decreases with decreasing oxygen content. For $T_c \leq 30$ K, $T^*$ approaches or becomes larger than 300 K.

The same analysis was done for several samples. The characteristic temperature dependence of in-plane resistivity is the same for equivalent doping levels. From diagrams like the one shown in Fig. 1 the phase diagram of these films as a function of doping can be established. As it is not possible to determine directly their oxygen content, the oxygen doping level is parameterized by the conductivity $\sigma_{ab}$ at 300 K which increases monotonically with it. By plotting $T_c$ and $T^*$, renormalized by $T_{cmax}$, against $\sigma_{ab}(300 K)/\sigma_{ab}(300 K)_{max}$, where $T_{cmax}$ and $\sigma_{ab}(300 K)_{max}$ are the values obtained for a given film at optimal doping, we obtain a unique phase diagram for all the films (Fig. 2). The doping dependence of $T^*$ is in good agreement with that reported from the transport study of a Bi-2212 single crystal examined in a more limited range of $T_c$ values ($T_c(R = 0) \geq 70$ K) [6]. Moreover the phase diagram shown in Fig. 2 is in very good agreement with the schematic phase diagram obtained by ARPES measurement of Bi-2212 single crystals [2]. The more rapid decrease of $\rho_{ab}(T)$ at $T^*$ appears to have the same physical origin as the opening of a pseudogap in the normal state spectrum shown by ARPES and closely related to the superconducting gap. Up to now, there is no consensus about the origin of the pseudogap effect: a precursor to the d-wave superconducting gap or a spin gap?

References