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Comparative Transport Studies of '1212' Superconductors

Albert Gapud[1]*, Judy Wu[2], Shaolin Yan[2], Yi-Yuan Xie[2], Byeongwon Kang[2], Michael Siega[3], and Don L. Overmyer[3]

[1]Institute of Mathematical Sciences and Physics
University of the Philippines Los Baños
4031 College, Laguna, Philippines
aag@physics.uplb.edu.ph
[2]Department of Physics and Astronomy
University of Kansas, Lawrence, Kansas, USA
[3]Sandia National Laboratories, Albuquerque, New Mexico, USA

ABSTRACT

$HgBa_2CaCu_2O_{6+\delta}$ (Hg-1212) thin films were fabricated by exchanging the Tl cations in $TlBa_2CaCu_2O_{7-\delta}$ (Tl-1212) thin films with Hg cations, causing a 30-K increase in Tc. To determine how this exchange effects such a Tc increase, the irreversibility lines, temperature dependence of critical current density, and temperature dependence of Hall angle of Hg-1212 and Tl-1212 thin films were measured and then compared. The results strongly suggest that the Tc shift is caused by a doubling of charge carrier density.

Keywords: Hg-1212, Tl-1212, transport, Hall effect, irreversibility.

INTRODUCTION

The purpose of this study (Gapud, 1999a) is to ascertain the nature of the 30-K shift in the critical temperature (T_c) in exchanging the Tl cation in $TlBa_2CaCu_2O_{7-\delta}$ (Tl-1212, $T_c \sim 90$ K) with the Hg cation to produce $HgBa_2CaCu_2O_{6+\delta}$ (Hg-1212, $T_c \sim 120$ K). This rare availability of high-quality samples of both '1212' species makes this study possible, and could shed new light on the still-unexplained mechanism of high-temperature superconductivity. Since the Hg-1212 films were fabricated from Tl-1212 by replacing Tl cations by Hg cations (Wu et al., 1999) the superconducting '1212' layered structured is preserved under this cation exchange; therefore the T_c shift is not due to the anisotropic layered structure prevalent in high-temperature superconductors, but more likely due to differences in the electronic structure and charge carrier density. It will be shown that the T_c shift is due primarily to a shift in charge carrier density.

EXPERIMENTAL DETAILS

The Hg-1212 thin films in this study were fabricated using a recently patented cation exchange process (Wu et al., 1999) in which Tl-1212 precursor films are converted into Hg-1212 films by surgically replacing Tl cations with Hg cations. The Tl-1212 films were fabricated using a modified crucible process (Siegal et al., 1998) in which DC-sputtered superconducting films were further improved by annealing in Tl vapor.

Two major studies were conducted. In the first (Gapud et al., 1999b; Gapud et al., 1999c), the irreversibility lines (IL's) of the '1212' species were measured using two independent methods. The first method used magnetic measurements, in which the applied field at

*Corresponding Author

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which magnetization becomes irreversible (H_{irr}) was interpolated from magnetization hysteresis loops measured at different temperatures using a Quantum Design superconducting quantum interference device (SQUID) magnetometer system with a maximum applied field of 5.5 Tesla. The second method used transport measurements, in which the irreversibility fields H^* were associated with the critical (zero-resistivity) temperature determined from resistivity-versus-temperature curves measured at different magnetic fields in the same SQUID system. In addition, the "magnetic" critical current density (J_c) for various '1212' films was calculated from magnetic hysteresis loops at different temperatures (Gapud et al., 1999c).

In the second part, Hall-effect measurements (Gapud et al., 1999d) were conducted in order to probe the scattering mechanism, as well as the nature of the charge carriers. These were done in an 8-Tesla Janus Superconducting Magnet system; both longitudinal (ρ_{xx}) and transverse (ρ_{xy}) resistivities were measured under cycled currents and magnetic field. From this data was calculated the Hall angle, $\cot\theta_H = \rho_{xx}/\rho_{xy}$.

DISCUSSION OF RESULTS

The results of the IL study showed for the first time that the IL's of two species of like anisotropy when plotted against normalized temperature T/T_c will

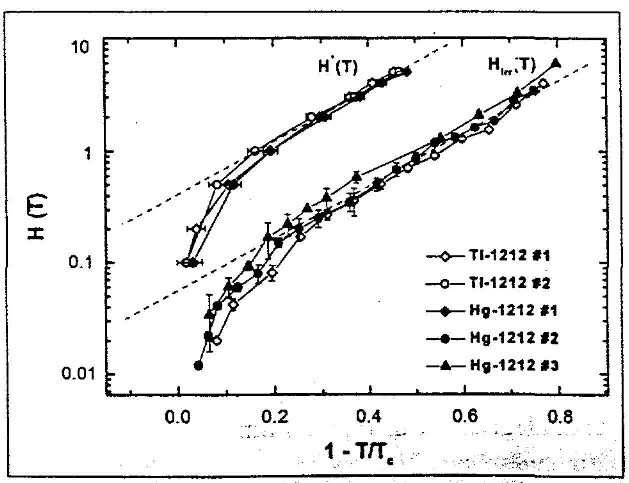

Fig. 1. Semi-log plot of transport-measured irreversibility lines (IL's) $H^*(T)$ and magnetically measured IL's $H_{irr}(T)$ for Hg-1212 and Tl-1212 thin films.

overlap. This is shown in Fig. 1, plotted in semilog scale to show that both transport and magnetic data also follow the same exponential decay law, $\exp[-\alpha(1-T/T_c)]$, where $\alpha > 0$ and α is *the same for both species*, as well as for different data sets of each species.

Another overlap occurs in a different part of the magnetic phase diagram, namely the critical current density $J_c(T)$ curves of the two species (i.e., *below* the irreversibility line) which *also* overlap at low fields when similarly normalized (Gapud, 1999c). These results are reminiscent of the well-known fact that intrinsic properties of BCS (isotropic) superconductors overlap when plotted against T/T_c. This occurs because the only difference between such materials is in their *order parameter*. It is similarly argued that the IL overlap of '1212' species is due significantly to a difference in order parameter.

Because the exchange of Hg and Tl cations causes a significant change in the distribution of oxygen in the lattice, it was suspected that this shift in the order parameter may be due to a shift in *the density of charge carriers* in the superconducting CuO_2 planes. To investigate this possibility, Hall-effect measurements were conducted in the normal state (Ong, 1990), primarily the Hall angle, $\cot\theta_H$. Previous studies (Wuyts, 1995) have shown that the slope of $\cot\theta_H(T^2)$ is linearly proportional to the two-dimensional charge carrier density in the CuO_2 planes and is therefore seen as a more reliable measure of charge carrier density, especially in light of the anomalous temperature dependence of Hall number, n_H. In the interest of making such a comparison of slopes, inverse Hall mobility, $H\cot\theta_H$, is plotted versus T^2 in Fig. 2. It turns out that the ratio of the slopes for the higher-T_c samples Hg#1 (120 K) and Tl#2 (90 K) is around two (2.03). This suggests that Hg-1212 has about *twice* the charge carrier density of Tl-1212, for samples close to optimal doping (as indicated by their close to optimal T_c).

An independent confirmation of this factor of two comes from assessing the characteristic temperature T^* below which the Hall angle data deviates from the usual $\sim T^2$ temperature dependence. In another study (Jin & Ott, 1998), T^* was shown to be proportional to the charge carrier density. In comparing reduced T^*/T_c for the present Hall data, the ratio for this quantity

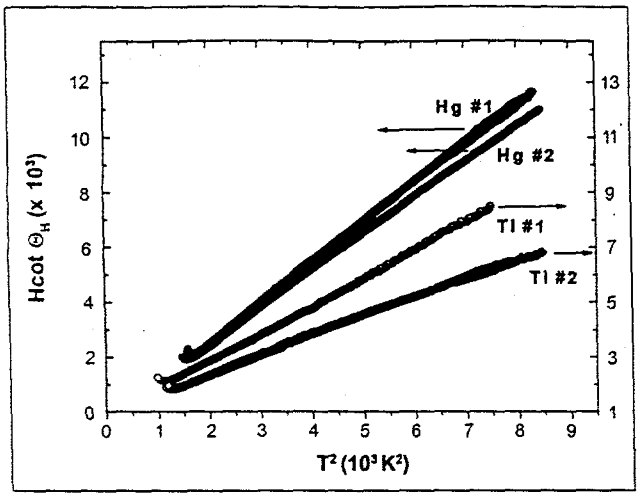

Fig. 2. Inverse Hall mobility ($\cot\theta_H$ times magnetic field) versus square of temperature for Hg-1212 and Tl-1212.

between Tl-1212 and Hg-1212 was found to be *also* around two (1.9).

From these comparative studies, it was found that (1) the irreversibility lines and critical current density of the '1212' species overlap when plotted against reduced temperature, implying that the shift in T_c is due mainly to a change in the order parameter, and that (2) this change in the order parameter is likely to be due to a *doubling* of the charge carrier density as a result of the cation exchange. This, in turn, opens the possibility that electronic structure, namely charge carrier density, may have a larger influence than lattice anisotropy in producing high critical temperatures (T_c) in these materials.

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