Measurements of $H_{c2}(T)$ in Bi–Sr–Cu–O


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$H_{c2}(T)$ has been measured for thin BSCO films at temperatures down to 65 mK and pulsed fields up to 35 T. $H_{c2}(T)$ diverged anomalously as the temperature decreased. At the lowest temperature, it was five times that expected for a conventional superconductor.

KEY WORDS: Upper critical field; BiSrCuO; anomalous critical field; $H_{c2}(T)$.

Measurements of $H_{c2}(T)$ for the high-temperature superconductors (HTS) have been limited to temperatures near $T_c$ because $H_{c2}$ in these materials rapidly exceeds accessible laboratory magnetic fields when the temperature is reduced to only nine-tenths of $T_c$. Thus, the values of $\xi$ calculated from such data calculated from the expression $H_{c2}(0) = \Phi_0 / (2\pi \xi^2)$, where $H_{c2}(0)$ is the upper critical magnetic field measured near $T=0$, require either a large extrapolation to $T=0$ K using a presumed functional form for $H_{c2}(0)$, from the slope $[dH_{c2}/dT]_c$, using the Werthamer–Helfand–Hohenberg (WHH) expression [1]: $H_{c2}(0) = 0.7T_c [dH_{c2}/dT]_c$. If, for some reason, $H_{c2}$ should depart from the expected theoretical behavior, then this procedure could be subject to unanticipated error.

Furthermore, the superconductive transitions are generally broadened in an applied magnetic field [2–6], which introduces ambiguity in choosing $H_{c2}$. For instance, $R(T, H)$ data on REBaCuO [3–5] yielded a nonlinear slope to $H_{c2}(T)$ near $T_c$. However, magnetization measurements on YBa$_2$Cu$_3$O$_{7-\delta}$ single crystals near $T_c$ for the field applied both parallel [7] and perpendicular to the $c$-axis yielded the expected linear behavior of $H_{c2}$ near $T_c$ from which $H_{c2}(0)$ has been calculated using the WHH expression. The magnetization results are more reliable because there is less ambiguity in defining $H_{c2}$ than in the former case. Similar anomalous results have been obtained in several of the HTS and have been generally dismissed as being due to vortex dynamics [3,8–13].

In this paper we report $H_{c2}(T)$ data on a high-quality thin film of Bi$_2$Sr$_2$CuO$_y$. The measurements extend down to a reduced temperature, $t = T/T_c$, of $t = 0.005$ and magnetic fields as high as 35 T. We observed a striking divergence in $H_{c2}(T)$ as $T$ approached zero. Recent results on Tl$_2$Ba$_2$CuO$_x$ crystals show the same behavior [14]. We find that such a divergence cannot be rationalized by any of the conventional or unconventional models for the behavior of superconductors in a magnetic field and thus requires the development of a new physical theory.

The Bi$_2$Sr$_2$CuO$_y$ system is an excellent choice for studying $H_{c2}(T)$ of a copper oxide superconductor. It has a comparatively simple structure (no chains, one CuO layer). Also, the superconducting properties are easily modified by varying the Bi–Sr ratio. $T_c$ is relatively low and thus the superconducting transitions are not significantly broadened in a magnetic field (flux dynamic broadening effects are small). Furthermore, $H_{c2}(T)$ is within laboratory reach over a very broad range of temperatures.
The superconducting phases of the \(\text{Bi}_2\text{Sr}_2\text{CuO}_y\) system are actually Sr deficient [15–17]. While bulk superconducting samples (both “single crystals” and polycrystalline) have been studied [15 17] they are difficult to prepare in pure form owing to the tendency to also generate the stoichiometric compound \(\text{Bi}_2\text{Sr}_2\text{CuO}_y\), which is a monoclinic insulating phase [15,16]. Superconducting films were successfully made using atomic, layer-by-layer, molecular-beam evaporation (ALL-MBE) [18], where the chemical composition is carefully controlled. Films of \(\text{Bi}_2\text{Sr}_2\text{CuO}_y\) approximately 1000 Å thick were grown on SrTiO\(_3\) substrates and subsequently patterned into a geometry suitable for resistance measurements.

The resistive transition of the film in zero magnetic field indicated that the superconductive transition began at a temperature of 19 K and extended down to 12 K where the transition was complete. When the magneto-resistance was measured, the film was oriented with its c-axis parallel to the applied field. The resistance was measured using a standard four-probe ac (excitation frequency 100 kHz, applied current 0.4 μA) technique as the magnetic field was pulsed from zero to 35 T. The magnetic field reached its maximum value 70 ms after pulse initiation, and it subsequently decayed to zero in 800 ms. Data were recorded during both periods to check for errors due to thermal drifts caused by heating or for error signals induced by transient effects. The measured resistance was essentially the same in both cases, indicating that these effects were not significant. Measurements were made at temperatures as low as 1.6 K in a pumped \(^4\)He cryostat. The sample was then transferred into another cryostat which contained a plastic dilution refrigerator in which the sample could be cooled down to 65 mK.

Figure 1 shows a series of \(R(H, T)\) curves for temperatures varying from 13 K down to 65 mK. These curves indicate that the transition widths are relatively insensitive to the applied field strength and that the quenched, normal-state resistance increases below \(T_c(H = 0)\). We define \(H_{c2}\) for each curve as the magnetic field where the extrapolated normal-state resistance and the tangent of the transition meet (Fig. 2, inset). Because the transition is not significantly broadened by the magnetic field, we have shown that any choice of position on the \(R(H, T)\) curve defines \(H_{c2}(T)\) curves with essentially the same shape.

Many of the early critical field measurements of the HTS have been questioned because the \(R(T)\) curves broaden significantly in a magnetic field due to flux dynamics. Roesler et al. [19] have performed tunneling measurements on \(\text{Ba}_{1-x}\text{K}_x\text{BiO}_3\) films in magnetic fields and were able to extract the Pauli-limited \(H_{c2}(T)\) curve. They also measured \(R(H, T)\) for the same sample. They concluded that \(H_{c2}(T)\) defined by the \(R(H, T)\) curve corresponded to the one obtained from tunneling if the former was defined near the “top” of the transition. Therefore, in this work, \(H_{c2}(T)\) is defined as shown in the inset of Fig. 2 which yields values that are virtually identical to a 10% resistance drop criterion.

Figure 2 displays the \(H_{c2}(T)\) data extracted from the \(R(H, T)\) data shown in Fig. 1. The conventional WHH curve, matched at \(dH_{c2}(T_c)/dT\), is shown for comparison. That slope is estimated to be 0.29 T/K so that \(H_{c2}(0)\) is calculated to be 3.8 T. This value of \(H_{c2}(0)\) corresponds to a coherence length of \(\sim 55 \text{ Å}\) in the \(ab\) plane.

The curves measured here have several features in common with measurements on the \(\text{Nd–Ce–Cu–O}\) [11] and \(\text{Sm–Ce–Cu–O}\) [12,13] systems in that the...