Upper critical magnetic fields of $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ single crystals

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Abstract

The upper critical magnetic fields of $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ single crystals with the applied magnetic fields H parallel to the ab -plane, $H_{c2}(ab)$, and perpendicular to the ab -plane, $H_{c2}(c)$, have been determined from the AC electrical resistivity measurements up to 8 T. Both $H_{c2}(ab)$ and $H_{c2}(c)$ exhibit positive curvature as a function of temperature T for $H_{c2} \leq 2$ T which is much pronounced in $H_{c2}(ab)$. The initial slopes $(-dH_{c2}/dT)_{T_{c0}}$ determined from the linear portion of the H_{c2} versus T curves have the values of 5.0 T/K for $H_{c2}(ab)$ and 1.6 T/K for $H_{c2}(c)$. Both $H_{c2}(ab)$ and $H_{c2}(c)$ data can be fitted very well by the conventional Werthamer, Helfand, Hohenberg and Maki (WHHM) theory in the minimum paramagnetic limit ($\lambda_{\infty} = \infty$) using the experimental values of the initial slopes $(-dH_{c2}/dT)_{T_{c0}}$ and T_c 's and indicates an ordinary type superconductivity in this system. The value of the anisotropic ratio obtained from the $H_{c2}(T)$ data and the $(-dH_{c2}/dT)_{T_{c0}}$ data is about 3.3.

The discovery of superconductivity with transition temperatures above the liquid nitrogen temperature in the $\text{RBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ($R = \text{Y}$ and rare earth) [1–9], Bi-Sr-Ca-Cu-O [10,11], and Tl-Ba-Ca-Cu-O [12,13] systems has attracted a lot of research activity. Since the upper critical magnetic field $H_{c2}(T)$ is a very important property for the type-II superconductors, investigations for determining the $H_{c2}(T)$ of the above systems on both polycrystalline and single crystalline high- T_c copper oxide compounds have been performed by many researchers. $H_{c2}(T)$ data for the polycrystalline samples of the $\text{RBa}_2\text{Cu}_3\text{O}_{7-\delta}$ systems reveal large values of the initial slopes $(-dH_{c2}(T)/dT)_{T_{c0}}$ (ranging from 2 to 4 T/K), and the extrapolated values of $H_{c2}(0)$ are about 100 to 250 T [14–20]. Moreover, measurements on the single-crystalline $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ samples show the anisotropic characteristic of a quasi-two-dimensional superconductor with $H_{c2}(c)/H_{c2}(ab) \approx 2\text{--}5$ [21,22]. For the Bi-Sr-Ca-Cu-O compounds, the obtained values of $(-dH_{c2}(T)/dT)_{T_{c0}}$ and $H_{c2}(0)$ are also

very large [23–28] and $H_{c2}(T)$ data of the $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals show a stronger 2D behavior [23–27]. Since the superconducting transition temperature T_{c0} is quite high in these compounds and the above data are usually taken with the magnetic fields $H \leq 25$ T and the suppression of T_c is usually not very significant, the results inferred from them are therefore not very promising. This can be shown in the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ system where $H_{c2}(T)$ has been measured up to $H > 100$ T for the single-crystalline sample which shows a bend over in the $H_{c2}(T)$ curves at high fields and the values of $H_{c2}(0)$ are much less than have been reported [29]. Moreover, since most of the existing data for the high- T_c copper oxide systems are in the temperature range of $t \geq 0.85$ ($t \equiv T_c(H)/T_c(H=0)$), they cannot be used for comparison with the existing theories for $H_{c2}(T)$. Therefore, it is very helpful to have H_{c2} data in the low- t region for better understanding of the superconducting properties in these high- T_c oxides.

The series of superconducting Bi-Sr-Ca-Cu-O

systems can be expressed as $\text{Bi}_2\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_x$ with $n=1, 2, 3$ and $x \approx 2n+4$. The superconducting transition temperature T_c for the $n=1$ ($\text{Bi}_2\text{Sr}_2\text{CuO}_6$) phase is much lower than that of the $n=2$ ($\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$) and $n=3$ ($\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$) phases. Therefore, much lower values of $H_{c2}(T)$ for $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ may be expected, and we can get the H_{c2} data down to much lower values of t without going to ultrahigh magnetic fields. This allows us to investigate the anisotropic behavior of this system from both $H_{c2}(T)$ curves and the initial slopes instead of from only the initial slopes as for most of the other high- T_c copper oxide superconductors. Moreover, by fitting the experimental data with the existing theories for $H_{c2}(T)$, we can get better information about the superconducting properties in the system. Since $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ compound also contains Cu–O layers as the superconducting layers and the Cu–O layers are also responsible for the occurrence of superconductivity in the high- T_c copper oxide systems, $H_{c2}(T)$ study of this compound should provide us with valuable information for a better understanding of the superconducting properties of the high- T_c superconductors.

The $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ single crystals were grown using a flux method from the off-stoichiometric mixtures ($\text{Bi}:\text{Sr}:\text{Cu}=2:2:1.5$ and $2:2:2$). We followed the processes as described in Ref. [30] to grow the single crystals. The cleaved crystals were further annealed under various conditions in order to have the best sample for the $H_{c2}(T)$ studies. The $H_{c2}(T)$ data in this study were determined from the AC electrical resistance measurements performed in a helium dewar using a four-wire resistance bridge operating at 16 Hz. A calibrated Ge thermometer was used for the zero-field measurement and for the calibration of a capacitor thermometer which was used as the thermometer for the non-zero field measurements up to $H=8$ T in this study.

The superconducting and normal state properties of the $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ single crystals are very sensitive to the annealing conditions. Shown in Fig. 1 are the normalized resistance $R(T)/R(300\text{ K})$ versus temperature T curves with the applied current along the ab -plane for the crystals annealed in flowing O_2 at various annealing temperatures T_{ann} . A small variation of the annealing temperature T_{ann} can cause dramatic change in the $R(T)/R(300\text{ K})$ behavior in the normal state and the superconducting transition temper-

Fig. 1. Normalized resistance $R(T)/R(300\text{ K})$ vs. temperature T curves with the applied current I along the ab -plane for the crystals annealed in flowing O_2 at various annealing temperatures T_{ann} .

ature T_c . The superconducting sample can be obtained with $T_{\text{ann}} \geq 800^\circ\text{C}$. The sample quality can be improved by increasing T_{ann} slightly and the best quality sample is obtained with $T_{\text{ann}}=805^\circ\text{C}$. For this sample, the resistance decreases linearly with decreasing T above 30 K and superconductivity occurs at ≈ 7 K with a transition width $\Delta T \approx 1$ K. The RR ratio for this sample is ≈ 8 and is larger than that of the other high- T_c oxides. Further increasing of T_{ann} will degrade the superconductivity and change the normal state resistance from metal-like to semiconducting-like behavior and superconductivity is destroyed for $T_{\text{ann}} \geq 808^\circ\text{C}$. In the subsequent studies we have chosen the crystals with $T_{\text{ann}}=805^\circ\text{C}$.

Shown in Fig. 2(a) are selected curves for resistance R as a function of temperature T in different applied magnetic fields H below 8 T for the single-crystal samples of $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ with the applied current along the ab -plane for $2\text{ K} \leq T \leq 10\text{ K}$. The $R(T)$ curves with H parallel to the ab -plane are displayed in Fig. 2(a). Superconducting transition occurs at 7 K with $T_c(50\%)=6.1$ K and the transition width $\Delta T_c=1.7$ K at zero magnetic field. The value of $T_c(50\%)$ is lower and ΔT_c is broader than those of the sample displayed in Fig. 1. This is probably due to the small variation of the furnace temperature. With increasing magnetic field, the superconducting transition curves shift to lower temperature and the transition widths increase. Superconductivity still persists up to $H=8$ T with $T_c(50\%)=2.5$ K. The

Fig. 2. (a) The $R(T, H)$ curves with H parallel to the ab -plane. (b) the $R(T, H)$ curves with H perpendicular to the ab -plane.

$R(T)$ curves in selected applied magnetic fields with H perpendicular to the ab -plane are shown in Fig. 2(b). The effect of the magnetic field in degrading the superconductivity is much stronger. For $H \geq 5$ T, superconductivity is destroyed. The broadening of the resistive transition with increasing magnetic field H is similar to that of the high- T_c superconductors such as $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ and is probably due to the variations in oxygen composition in the samples. Unlike the high- T_c copper oxides, the normal state resistance in $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ is not sensitive to the applied magnetic field H and allows us to determine the H_{c2} more precisely.

The H_{c2} versus T data for H parallel to the ab -plane determined from the above resistivity measurements are plotted in Fig. 3 with the open circles representing the data with the superconducting transition temperature T_c defined as the temperature where the resistance drops to 90% of its extrapolated normal state resistance value ($T_c(90\%)$), the solid spheres represent the $H_{c2}(T)$ data for $T_c(50\%)$, and the crosses represent the $H_{c2}(T)$ data for $T_c(10\%)$. Both $H_{c2}(ab)$ and $H_{c2}(c)$ exhibit positive curvature as a function

Fig. 3. $H_{c2}(T)$ data with H parallel to the ab -plane and with the superconducting transition temperatures defined as $T_c(90\%)$, $T_c(50\%)$, and $T_c(10\%)$, respectively. The solid lines are calculated from the WHM theory with $\lambda_{so}=0$ and $\lambda_{so}=\infty$.

of temperature T for $H_{c2} \leq 2$ T, which is much pronounced in $H_{c2}(ab)$. It is possible that the positive curvature is due to the field dependence of the transition width. However, a careful inspection of the experimental data shows that in fact this positive curvature in H_{c2} versus T is independent of how T_c is defined. A concave behavior in the $H_{c2}(T)$ at low fields has also been observed in the high- T_c superconductors and it has been argued by many authors that it may be due to the so-called thermally assisted flux flow.

The initial slopes $(-dH_{c2}/dT)_{T_{c0}}$ determined from the linear portion of the H_{c2} versus T curves for $H_{c2}(ab)$ have the values of 5 T/K for $T_c(90\%)$ and 3.7 T/K for $T_c(50\%)$, respectively. A lower value of the initial slope is obtained if we take the low field data due to the concave curvature near T_{c0} . The standard curves calculated from the Werthamer, Helfand, Hohenberg and Maki (WHHM) theory [31,32] of $H_{c2}(T)$ for the conventional type-II superconductors using the experimental values of the initial slopes $(-dH_{c2}/dT)_{T_{c0}}$ and T_c 's for the minimum ($\lambda_{so}=\infty$) paramagnetic limit, where λ_{so} is the spin orbit scat-

tering parameter, are also plotted in Fig. 3. Except for the positive curvature region, the calculated $H_{c2}(T)$ curves fit the experimental data quite well in the entire temperature range. The calculated upper critical fields at zero temperature $H_{c2}(0)$ are 22 T for H_{c2} determined from $T_c(90\%)$ and 11.6 T for H_{c2} determined from $T_c(50\%)$. For comparison, the calculated curves in the maximum ($\lambda_{so}=0$) paramagnetic limit are also plotted. These curves deviate from the experimental data at high fields and yield lower values of $H_{c2}(0)$. It is noticeable that only one adjusting parameter, λ_{so} , is used in the curve fitting. This indicates that superconductivity in this system is possibly of the ordinary type. The orbital critical magnetic field at absolute zero as estimated from the formula $H_{c2}^*(0) = -0.69T_{c0} (dH_{c2}/dT)_{T_{c0}}$ for $T_c(50\%)$ is 16 T (11.6 T if a value of T_{c0} extrapolated from the calculated curve is used) and the coherence length at zero temperature can be estimated from $\xi_0^2 = \Phi_0/2\pi H_{c2}^*(0)$, where $\Phi_0 = ch/2e = 2.07 \times 10^{-7}$ Oe cm² is the flux quantum, and yields a value of 17 Å.

To see the anisotropic behavior of the $H_{c2}(T)$, we have plotted in Fig. 4 the $H_{c2}(T)$ data obtained from

Fig. 4. $H_{c2}(ab)$ and $H_{c2}(c)$ plotted as a function of temperature T with the superconducting transition temperatures defined as $T_c(90\%)$. The solid lines are calculated from the WHM theory with $\lambda_{so} = \infty$.

$T_c(90\%)$ with H parallel (open circles) and perpendicular to (solid spheres) the ab -plane. The value of $-(dH_{c2}/dT)_{T_{c0}}$ determined for $H_{c2}(c)$ is 1.6 T/K. The calculated curves (solid curves) from the WHM theory for $\lambda_{so} = \infty$ are also plotted. Again, the fitting is quite good for $H_{c2}(c)$. The estimated values of $H_{c2}(0)$ from the calculated curves are 22 T for $H_{c2}(ab)$ and 6.6 T for $H_{c2}(c)$. The anisotropic ratios obtained from the $H_{c2}(T)$ curves and from the values of the initial slopes yield a similar value of ≈ 3.3 .

The values of the initial slopes and the anisotropic ratio of $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ are close to those of the single-crystalline $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ samples and are much smaller than those of the $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals. This indicates that the quasi-two-dimensional characteristic for $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ is similar to that of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and is weaker than that of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$. A possible reason may be the insertion of the Ca atoms between the Cu–O layers for $n=2$ and that there are only five nearest oxygen atoms for each Cu atom, while for $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ and $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ there are six nearest oxygen atoms for each Cu site. This one extra oxygen atom perpendicular to the Cu–O layers may play a role in determining the anisotropic characteristic in the superconducting state for the oxide superconductors. Since all the high- T_c oxides contain Cu–O layers as the superconducting layers, our results indicate that it is possible that the WHM theory is suitable for describing their $H_{c2}(T)$ behaviors.

In summary, we have investigated the $H_{c2}(T)$ for the single-crystalline samples of $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ resistively up to a magnetic field of 8 Tesla. The initial slopes for H along the ab -plane and H perpendicular to the ab -plane are 5.0 T/K and 1.6 T/K, respectively. We found that the $H_{c2}(T)$ data can be fitted very well by the conventional WHM theory, which indicates that superconductivity in this compound is of the ordinary type. The value of the anisotropic ratio obtained from the $H_{c2}(T)$ data and $(-dH_{c2}/dT)_{T_{c0}}$ data is about 3.3.

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