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Penetration Depth of $Tl_2Ba_2Ca_2Cu_3O_y$ and $Tl_{0.58}Pb_{0.4}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_y$ Bulk Superconductors

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The penetration depths of bulk $Tl_2Ba_2Ca_2Cu_3O_y$ and $Tl_{0.58}Pb_{0.4}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_y$ superconductors with the critical temperatures 112 K and 114 K, respectively, were determined from the AC susceptibility measurements. When the samples are in the Meissner state, the dispersive components of AC susceptibility as well as their temperature dependences reflect the changes of the penetration depths at various temperatures. In these bulk ceramic superconductors the penetration depths are of the order of few μm and they are comparable to the grains sizes in the ceramics.

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1. Introduction

Magnetic field can penetrate into high-temperature superconductors generally in two ways. At low temperatures and small magnetic fields, the sample is in the Meissner state and magnetic field penetrates it only to the small depth below sample surface, called as the London penetration depth λ — one of the most important microscopic parameters of the superconducting materials. At higher temperatures and in higher magnetic fields the superconductors are in the mixed state and magnetic field penetrates the centre of the sample via the motion of vortices. Measurements of two components of AC susceptibility versus temperature give information about the processes of magnetic field penetration into the sample. In the measurements taken at small AC field amplitudes and generally at low temperatures only dispersive component occurs — the superconductor is in the Meissner state. On the other hand at high temperatures, close to the superconducting transition temperature T_c, as well as at high magnetic field amplitudes, the absorption component of susceptibility has non-zero value and forms characteristic peak due to magnetic field losses caused by the vortices motion in the sample. From the point of view of penetration depth determination, interesting for us are the measurements taken at small H_{AC} and at low temperatures, where the absorption component of susceptibility $\chi''(T)$ is equal to 0 while the dispersive component $\chi'(T)$ reaches its maximal values.

The penetration depth is usually calculated by indirect methods. A lot of experimental methods such as AC susceptibility [1], surface impedance [2], infrared transition and reflectivity [3], magnetization in low fields (in the Meissner state) [4] as well as in higher fields (in the mixed state) [5], muon spin rotation [6], electron spin resonance (ESR) [7], magnetic force microscopy (MFM) [8] and other have been used to determine the penetration depth in bulk and thin films superconductors. There are a few direct methods of determining the penetration depths like that presented in the paper [9]. The penetration depths of high temperature superconductors (HTS) change in the wide range. The typical values of the penetration depths vary from tens nm for the LSCO system with small strontium doping [10], hundred nm for YBCO single crystals [11] to a few μm for thallium based single crystal [12].

In this paper the novel methods of determination of the penetration depth are presented and used for ceramic $Tl_2Ba_2Ca_2Cu_3O_y$ and $Tl_{0.58}Pb_{0.4}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_y$ superconductors.

2. Experimental

Ceramic superconductors of $Tl_2Ba_2Ca_2Cu_3O_y$ and $Tl_{0.58}Pb_{0.4}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_y$ were fabricated from spray dried nitrates [13] and from malate gels methods [14], respectively. The samples were cut and thinned to obtain the rectangle shape with the dimensions: width — 2 mm, length — 10 mm, thickness — from 0.04 to 0.2 mm. The magnetic field was parallel to the sample length so one dimension d of the cross-section perpendicular to the magnetic field could be neglected in the calculations of the λ (see Fig. 1).

The dispersion χ' and absorption χ'' parts of the AC susceptibility as a function of temperature in low magnetic field amplitudes were measured by a standard mutual inductance bridge operating at the frequency of 189 Hz. A Stanford SR 830 lock-in nanovoltmeter served both as a source for the AC current for the coil which produced the AC magnetic field and as a voltmeter of the bridge. The temperature was monitored by a Lake

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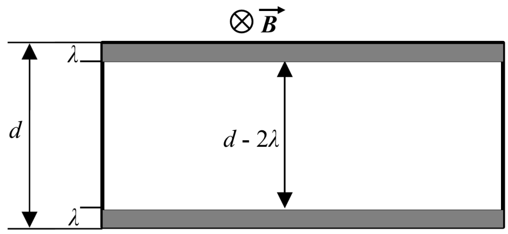

Fig. 1. Superconducting slab of the thickness d in the magnetic field that enters into this sample on the depth λ.

Shore temperature controller employing a chromel-gold – 0.07% Fe thermocouple with an accuracy of ±0.05 K for this experimental setup.

3. Methods, results and discussion

To get the penetration depth the two methods were used in the way as follows.

3.1. Method 1

Penetration depth was calculated from the relation of the fraction of the sample volume where the magnetic field is fully screened to the total volume of the sample (perfect diamagnetism). It corresponds to the relation of the magnetic susceptibility: $\chi'_{\text{max}}/\chi'_{\text{theor}}$, where χ'_{max} is the maximal value of the dispersive component of susceptibility at low temperatures plateau and χ'_{theor} is the theoretical susceptibility in the case of ideal diamagnetism

$$\chi_{\text{theor}} = -\frac{1}{4\pi\rho(1-n)}, \quad (1)$$

where ρ is the sample density determined from the mass and dimensions of the sample and n is the demagnetization factor.

According to Fig. 1 and the relation

$$\frac{\chi'_{\text{max}}}{\chi'_{\text{theor}}} = \frac{V_{\text{screened}}}{V_{\text{total}}}, \quad (2)$$

the penetration depth for the flat samples can be calculated from the formula

$$\lambda = \frac{d}{2}\left(1 - \frac{\chi'_{\text{max}}}{\chi'_{\text{theor}}}\right), \quad (3)$$

where d is the sample thickness.

3.2. Method 2

Penetration depth can be also determined from the temperature dependence of the dispersive component of the susceptibility of the sample in the Meissner state. From the formula (3), we can calculate the susceptibility

$$\chi'_{\text{max}}(T) = \chi'_{\text{theor}} - \frac{2\chi'_{\text{theor}}}{d}\lambda(T). \quad (4)$$

Next, we implement the temperature dependence of λ from the two-fluid model [15] and we get

$$\chi'_{\text{max}}(T) = \chi'_{\text{theor}} - \frac{2\chi'_{\text{theor}}}{d}\lambda(0)\left(1 - \left(\frac{T}{T_c}\right)^4\right)^{-\frac{1}{2}}, \quad (5)$$

So, we can fit the temperature dependence of dispersive component of susceptibility with the formula

$$\chi'(T) = A - B\left(1 - \left(\frac{T}{T_c}\right)^4\right)^{-\frac{1}{2}}, \quad (6)$$

with the fitting parameters: $A = \chi'_{\text{theor}}$, $B = \frac{2\chi'_{\text{theor}}}{d}\lambda(0)$ and T_c. After that, the penetration depth $\lambda(0)$ can be calculated from the relation

$$\lambda(0) = \frac{Bd}{2A}. \quad (7)$$

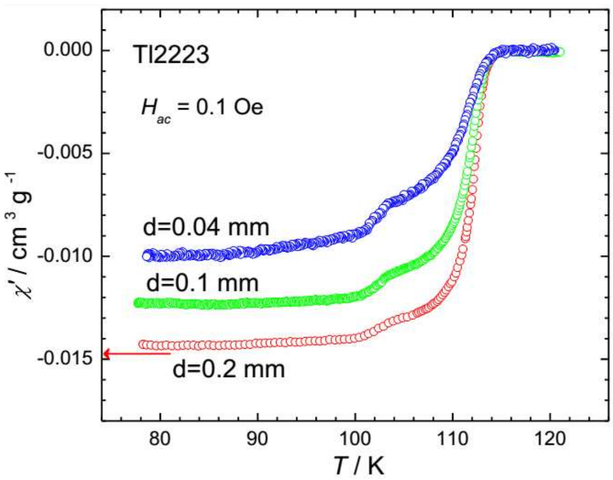

Fig. 2. Dispersive component of the susceptibility for the bulk $Tl_2Ba_2Ca_2Cu_3O_y$ high-T_c superconductor.

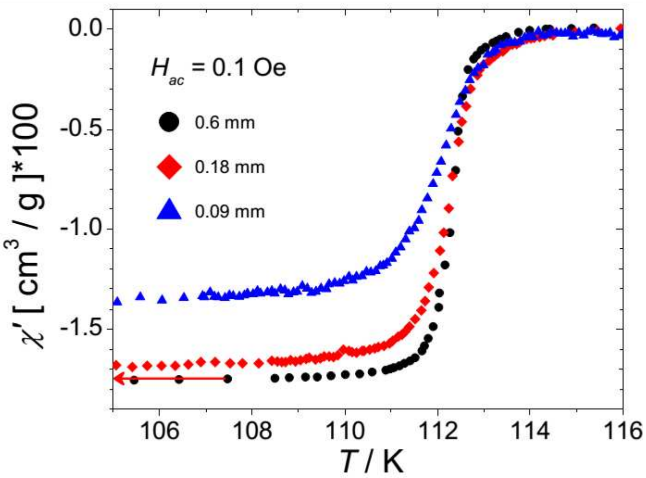

Fig. 3. Dispersive component of the susceptibility for the bulk $Tl_{0.58}Pb_{0.4}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_y$ high-T_c superconductor.

Figures 2 and 3 present the temperature dependences of susceptibility for the superconductors $Tl_2Ba_2Ca_2Cu_3O_y$ and $Tl_{0.58}Pb_{0.4}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_y$, respectively, obtained for different thickness of the samples. The red arrows show the values of the ideal diamagnetism calculated using the formula (1). The densities were obtained from the masses and dimensions of the samples. The calculated penetration depths for these samples are collected in Table I.

TABLE I

Penetration depths of the thallium based superconductors calculated from the maximal values of susceptibility $\chi'(T)$ according to the formula (3) for different sample thickness.

Sample	d [mm]	ρ [$\frac{g}{cm^3}$]	χ'_{theor} [$10^{-2}\ \frac{cm^3}{g}$]	λ [μm]
$Tl_{0.58}Pb_{0.4}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_y$	0.18	4.55	−1.78	5.5
$Tl_{0.58}Pb_{0.4}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_y$	0.09	4.55	−1.77	11.5
$Tl_2Ba_2Ca_2Cu_3O_y$	0.2	5.42	−1.50	4.1
$Tl_2Ba_2Ca_2Cu_3O_y$	0.1	5.42	−1.49	8.4
$Tl_2Ba_2Ca_2Cu_3O_y$	0.04	5.42	−1.48	6.4

The accuracy of this method is not good due to the fact that the relation $\chi'_{max}/\chi'_{theor}$ is close to 1 (see formula (3)) particularly for the samples with the thickness over 0.1 mm. It needs very precise measurements of the sample density (χ'_{theor}) as well as the χ'_{max} determination (the demagnetization factor influence). For the samples with the thickness of 0.1 mm and below we estimate the error of the λ to be about 2–3 μm.

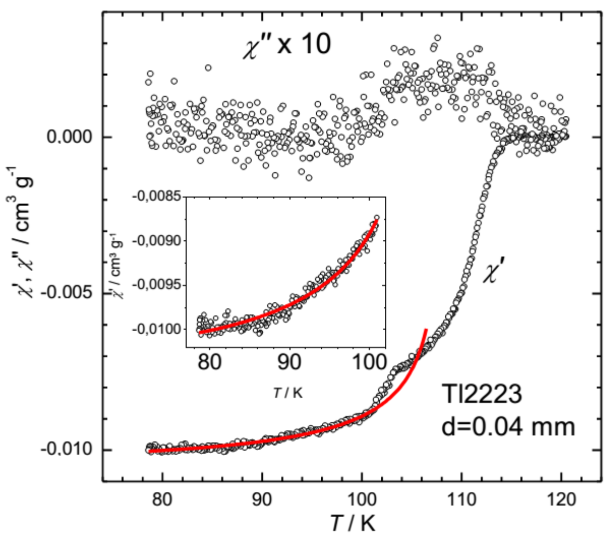

Fig. 4. Temperature dependences of the depressive component of AC susceptibility of $Tl_2Ba_2Ca_2Cu_3O_y$ (closed squares). (Inset) The low-temperature part of the $\chi'(T)$ was fitted with the formula (5) (solid line).

The second method is less sensitive to the problems described above. We measure the tendency of the dispersive component of the susceptibility behaviour in varying temperatures. The example fittings of the $\chi'(T)$ dependences for the thallium based superconductors are shown in Figs. 4, 5. Penetration depths of the thallium based

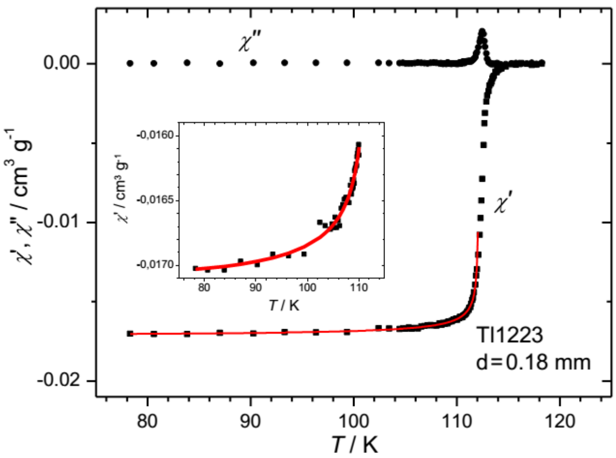

Fig. 5. Temperature dependences of the dispersive component of AC susceptibility of $Tl_{0.58}Pb_{0.4}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_y$ (closed squares). (Inset) The low-temperature part of the $\chi'(T)$ was fitted with the formula (5) (solid line).

superconductors obtained from the fitting the temperature dependences of the susceptibility $\chi'(T)$ according to the formula (5) for different sample thickness are listed in Table II.

TABLE II

Penetration depths of the thallium based superconductors obtained from the fitting of the temperature dependences of susceptibility $\chi'(T)$ according to the formula (5) for different sample thickness.

Sample	d [mm]	$\lambda(0)$ [μm]
$Tl_{0.58}Pb_{0.4}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_y$	0.18	1.9
$Tl_{0.58}Pb_{0.4}Sr_{1.6}Ba_{0.4}Ca_2Cu_3O_y$	0.09	7.8
$Tl_2Ba_2Ca_2Cu_3O_y$	0.04	2.6

4. Conclusions

The conclusions of the paper may be summarized as follows:

1. The penetration depths obtained for the bulk high-T_c superconductors are of the order of several μm. The values obtained for the samples with lower thickness (0.1 mm and less) are systematically higher in comparison to the data determined for the thicker samples. Nevertheless, they are comparable to the typical superconducting ceramics with the similar grain sizes. It suggests that screening currents flow only in the first layer of grains below the sample surface when the superconductor is in the Meissner state.

2. These methods are very sensitive to the measuring conditions such as the demagnetization factor, the determination of sample density etc.

3. Temperature dependences of the susceptibility reflect a good approximation to the two-fluid model only at low temperatures. The AC susceptibility in the vicinity of critical temperature does not fit to this model.

Acknowledgments

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