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Penetration Depth of Magnetic Field into $YBa_2Cu_3O_x$ Film on Polycrystalline Ag Substrate

R. Zalecki, W.M. Woch*, M. Chrobak and A. Kołodziejczyk
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science,
Solid State Physics Department, Cracow, Poland

The magnetic field penetration depth into $YBa_2Cu_3O_x$ film on polycrystalline Ag substrate with the critical temperature of 90.4 K was determined from the AC susceptibility measurements. The 95 μm thick YBCO film was deposited directly on Ag substrate by the sedimentation process. When the sample is in the Meissner state, the dispersive component of the AC susceptibility as well as its temperature dependence reflects the changes of the penetration depth with the temperature. The penetration depth of this film is found to be 5.4 μm.

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1. Introduction

Magnetic field can penetrate into high-temperature superconductors generally in two ways. At the low temperatures and the small magnetic fields a sample is in the Meissner state and the magnetic field penetrates it only to the small depth below the sample surface called as the London penetration depth λ — one of the most important microscopic parameters of the superconducting materials. At the higher temperatures and in the 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 the two components of ac susceptibility versus temperature give the information about the processes of magnetic field penetration into a sample. In the measurements we have taken at small ac field amplitudes and generally at the 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 in the 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 the penetration depth determination interesting for us are the measurements that have been taken at small H_{ac} and at the low temperatures where the absorption component of susceptibility $\chi''(T)$ is equal to zero while the dispersive component $\chi'(T)$ reaches its maximal values.

The penetration depth is usually obtained by indirect methods. A lot of experimental techniques 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) [9] and other have been used to determine the penetration depth in bulk and thin film superconductors. There are a few direct methods of determining the penetration depth like that presented in the paper [9]. The penetration depth of high temperature superconductors (HTS) changes in the wide range. The typical values of the penetration depths vary from tens nm for the LSCO system with small strontium doping [10] to quite a few μm for thallium based single crystals [11]. The penetration depth of YBCO superconductors depends on their critical temperatures as well as on the values of the oxygen parameters. The penetration depth of these compounds vary from 0.15 μm for $YBa_2Cu_3O_{6.95}$ (T_c = 93.2 K) [12, 13] through hundreds nm for YBCO single crystals [14] up to 7.8 μm for $YBa_2Cu_3O_{6.50}$ [15].

In this paper the novel method of calculation of the penetration depth is presented and used for the $YBa_2Cu_3O_x$ film that was deposited without any buffer layers on polycrystalline Ag substrate by the sedimentation process [16].

2. Experimental

Polycrystalline YBCO samples were prepared with the standard powder solid-state reaction technique. It consists of mixing of the copper and yttrium oxides and the barium carbonate in appropriate amounts. The mixed powders were sintered at 900 °C for the 20 h and then reground into fine powder. The mixing and sintering procedure was repeated to obtain more uniform phase of the superconducting powder. The relative low sintering temperature was used to obtain the superconducting powder with small grains. The powder was then mixed in the isopropanol to make the suspension. The starting suspension after 15 s of sedimentation process was poured to another vessel. The‘powder left on the bottom of the first vessel contained the largest grains (it was called as the first fraction). This procedure was repeated for the rest of the suspension to get the smaller grains fractions. The second fraction was obtained after 13 min of sedimentation, the third fraction — after further five and half hours and the fourth — from the rest of the suspension.

*corresponding author; e-mail: wmwoch@agh.edu.pl

The parts of the powders of each fractions were pressed to make the pellets and sintered in the temperature 900 °C and then slowly cooled down to the room temperature in the flowing oxygen. The ac susceptibility measurements showed that the first fraction pellet revealed the best superconducting properties. The powder of this fraction was used to make the superconducting film. It was mixed with isopropanol in a vessel with a silver substrate on its bottom. After evaporation of the alcohol the powder deposited on the silver substrate was pressed with the pressure of about 0.5 GPa. The film was put into furnace and sintered at 900 °C for two hours and then cooled down to 400 °C in the flowing oxygen atmosphere during 5 h. Finally, it was left at this temperature for 2 h for oxidation and then was cooled down slowly to the room temperature. The thickness of the film was measured using XRF spectrometer. The dimensions of the sample were $10 \times 6 \times 0.095$ mm^3.

The dispersion χ' and absorption χ'' parts of the ac susceptibility as a function of temperature in the low magnetic field amplitude of 0.5 Oe were measured by a standard mutual inductance bridge operating at the frequency of 18.9 Hz. The magnetic field was parallel to the film surface. 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 the Lake Shore temperature controller employing a chromel–gold–0.07%Fe thermocouple with an accuracy of ± 0.05 K for this experimental setup.

3. Method, results and discussion

Penetration depth can be 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 ratio: $\chi'_{\text{max}}/\ \chi'_{\text{theor}}$, 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

$$\chi_{\text{theor}} = -\frac{1}{1-n}, \tag{1}$$

where n is the demagnetization factor.

According to Fig. 1 and the relation

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

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

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

where d is the sample thickness.

When we cannot exactly determine the density and volume of the sample, we can calculate the penetration depth from the measurements of the χ'(T) behaviour at low temperatures and the low magnetic field amplitudes when the sample is in the Meissner state (i.e. the $\chi''(T)$ component is equal to zero).

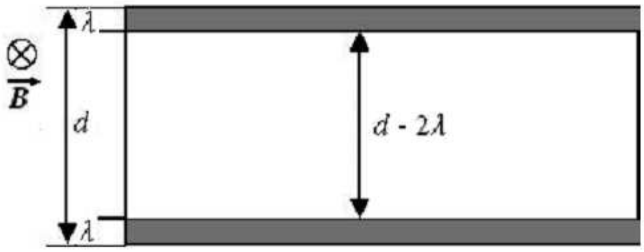

Fig. 1. Superconducting slab of the thickness d in the magnetic field that enters into this sample on the depth λ.

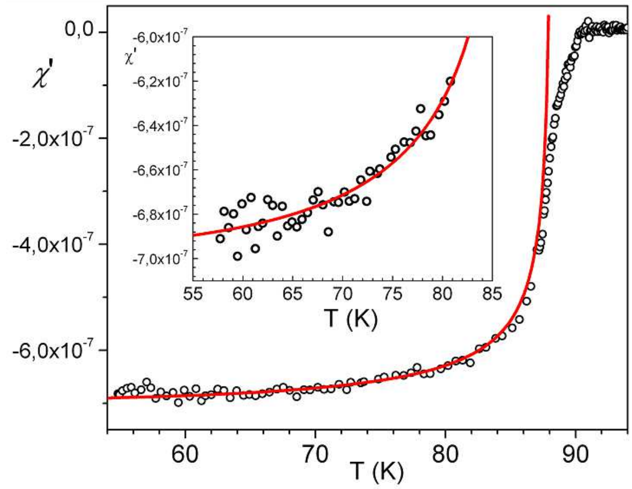

Fig. 2. Temperature dependences of the depressive component of ac susceptibility of $YBa_2Cu_3O_x$ film on polycrystalline Ag substrate (opened circles). The solid line represents the fit using Eq. (6). Inset: the low-temperature part of the $\chi'(T)$ fitted with the formula (6) (solid line).

From the formula (3) we can calculate the susceptibility

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

Next, we implement the temperature dependence of $\lambda(T)$ from the two-fluid model [17] and we get

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

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

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

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

$$\lambda(0) = \frac{B}{A}\cdot\frac{d}{2}. \tag{7}$$

The measurements was carried out in low magnetic field amplitude of 0.5 Oe. The susceptibility measurements showed good superconducting properties of the film with the critical temperature $T_c = 90.4$ K. The low temperature part of dispersive component of ac susceptibility was fitted with the formula (6) and we obtained the following parameters: $A = -7.87 \pm 0.34$, $B = -9.0 \pm 2.1$ and $T_c = 88.2 \pm 3.0$ K (see Fig. 2).

According to the formula (7) we can calculate the $\lambda(0)$ value:

$$\lambda(0) = 5.4 \pm 1.3\ \mu\text{m}.$$

The obtained value of $\lambda(0)$ concerns the bulk superconductor, not the grains, whose penetration depths are average one magnitude smaller than for the bulk samples.

4. Conclusions

The conclusions of the paper may be summarized as follows:

1. The good quality of $YBa_2Cu_3O_x$ film on polycrystalline Ag substrate without any buffer layers was obtained using the sedimentation process. The critical temperature determined from the ac susceptibility measurements is to be $T_c = 90.4$ K.

2. The penetration depth for the YBCO ceramic film was calculated to be $\lambda(0) = 5.4\ \mu$m. This value is comparable to the typical superconducting ceramics 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.

3. This method of determining the $\lambda(0)$ is very sensitive to the measuring conditions such as the demagnetization factor, and the sample orientation in magnetic field.

4. Temperature dependences of the susceptibility reflect a good approximation to the two-fluid model in the wide range below the critical temperature.

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