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Experimental study of the lower critical field in high-T_c-single crystals

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Employing SQUID magnetometry and novel measuring and evaluation techniques, precise information on the first penetration field can be obtained and used to extract H_{c1}. Tl- and Bi-based as well as a series of oxygen deficient Y-123 high T_c superconducting single crystals were investigated (H_{c1} || c). In all cases, H_{c1} is smaller than previously reported and can be described by BCS-theory.

1. INTRODUCTION

H_{c1} is one of the fundamental mixed state parameters of type II superconductors. It is not easily assessed in high T_c superconductors because of their anisotropic character and unavoidable pinning effects at low temperatures. Subtracting the measured moments from the initial Meissner slope [1] or an evaluation of the experimental magnetization curve in terms of flux pinning models [2] led to an unusual linear temperature dependence with large H_{c1}(0)-values [3]. The method to be presented, is based on the measurement of trapped moments by SQUID magnetometry, but takes advantage of characteristic features of the instrument employed and a specific evaluation routine, which leads to a significant enhancement of the overall resolution for the detection of the first flux penetration.

2. EXPERIMENTAL TECHNIQUE

The instrument employed is a commercial low field SQUID magnetometer MPMS2

(Quantum Design). It allows to keep undesired residual fields below 50 nT. Platelet-shaped single crystals were placed onto a U-shaped aluminum holder, which was inserted into an aluminum rod [4]. The experimental procedure is as follows: Firstly, the lowest possible residual field is established in the SQUID. Then, the sample is cooled to the first measuring temperature T₁. The field dependence of the trapped magnetic moment m_t is assessed through measuring cycles, consisting each of three measurements, as follows: Firstly, three scans are made in "zero" field, secondly, an external field H_a is applied and three scans are made at this field, and thirdly, the field is removed and the scanning repeated. The cycle is completed by heating above T_c and cooling back to the temperature T₁. Then, the next cycle is started with a slightly higher applied magnetic field H_{a, n+1}, etc. The first and third cycle provide us with the field dependence of the trapped moments. The SQUID signals recorded during these cycles are subtracted point by point. All unwanted contributions cancel and the resulting data points as a

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Fig. 1. Temperature dependence of H_{c1} .

function of the position can be inspected visually. The field, at which the response pattern corresponds to the curve expected for a sample containing a well defined magnetic moment, is identified as the first penetration field. Alternatively, the response patterns can be converted into magnetic moments m , and plotted versus H_a . The data scatter around zero, but clearly deviate above a certain field, which can again be identified as the first penetration field. Finally, the applied field is converted into the effective field $H_{a,e} = H_a / (1-D)$ and the first penetration field is then identified as the lower critical field H_{c1} . For a further discussion of the experimental technique see [5].

3. RESULTS

A variety of single crystals (TI-2223, TI-1223, Bi-2212, and Y-123 with various oxygen contents) were investigated. The experimental results are summarized in Table 1, where $H_{c1}(0)$ -data and the slope of H_{c1} at T_c are listed. The $H_{c1}(T)$ -data are analyzed in terms of BCS and strong coupling clean-limit theory [6]. Typical results are shown in Fig. 1 for a TI-2223 single crystal. We find very good agreement with BCS theory, whereas

Table 1

Summary of results for $H_{c1}(0)$ and the slope of H_{c1} at T_c ($H || c$):

	$\mu_0 H_{c1}(0)$ (mT)	$-\mu_0 H_{c1}(T_c)$ (mT/K)
TI-2223	8.9 ± 0.3	0.17
TI-1223	24.7 ± 0.7	0.62
Bi-2212	33 ± 1	0.9
$YBa_2Cu_3O_{7-x}$	17.6 ± 0.5	0.45
$YBa_2Cu_3O_{6.4}$	13.6 ± 0.4	0.58
$YBa_2Cu_3O_{6.1}$	3.4 ± 0.1	0.44

the strong coupling clean-limit data are somewhat lower.

4. SUMMARY

We show that the assessment of the first penetration field can be improved significantly by employing specific measuring routines and evaluation procedures. The method is based on the determination of the first appearance of a trapped magnetic moment in the superconductor. The improvements refer to specific features of the magnetometer and of the evaluation procedures. The results obtained on a series of high T_c single crystals show in all cases a smooth temperature dependence without pronounced upturns. In general, the temperature dependence can be very well described by BCS theory (weak-coupling, clean-limit).

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