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PEAK-EFFECT, SCALING BEHAVIOR AND VOLTAGE-CURRENT CHARACTERISTICS FOR $TmBa_2Cu_3O_{7-\delta}$ SINGLE CRYSTAL

A.A.Zhukov[a], H.Kupfer[b], S.A.Klestov[a], V.I.Voronkova[a], V.K.Yanovsky[a]

[a] Physics Department, Moscow State University, Moscow 117234, Russia
[b] Kernforschungszentrum Karlsruhe, Institute fur Technische Physik, Postfach 3640, W-7500 Karlsruhe, FRG

ABSTRACT

The peak-effect in the nearly untwinned $TmBa_2Cu_3O_x$ single crystal has been studied. Two magnetic field intervals corresponding to different behaviors of shielding currents j_s were found. The current-voltage characteristics extracted from the magnetization measurements are described by the powerlike relation $E \sim j_s^n$ with n being dependent on temperature and magnetic field. Possible reasons of the observed behavior are discussed.

INTRODUCTION

One of the most interesting peculiarities of the magnetization hysteresis in HTSC behavior is a peak-effect, called sometimes as a "fishtail" or "butterfly" effect due to the specific shape of a hysteresis curve [1-3]. However, its scaling behavior and the dependence on the sweep rate of magnetic field have not been studied yet. These studies in combination with the magnetization relaxation data would allow to discriminate different pinning mechanisms and give the information about current voltage characteristics of the sample.

In this work the peak-effect for the nearly untwinned $TmBa_2Cu_3O_{7-\delta}$ single crystal is studied. The dependences of the shielding currents on magnetic field, its sweep rate and temperature are analysed. The existence of two regions which possess different scaling behaviors is found.

SAMPLE PREPARATION AND MEASUREMENTS PROCEDURE

The studied $TmBa_2Cu_3O_x$ single crystal with the dimensions 0.93x0.67x0.16 mm^3 was grown from non-stoichiometric melt in the system Tm_2O_3-BaO-CuO(Cu_2O) [4]. This procedure allows to obtain essentially twin-free crystals in as grown state. The twin structure was controlled by optical microscopy in polarized incident light and by the X-ray analysis. Both methods proved that the relative volume of twins with the orientation different from the main one was less than 2÷3%. The transition temperature determined from the diamagnetic signal appearance was ~ 90K.

Measurements of magnetic properties were made for the orientation of magnetic field H‖c using a vibrating sample magnetometer.

RESULTS OF MEASUREMENTS AND DISCUSSION

The density of shielding currents was determined on the basis of Bean model [5] to be good approximation for steep enough voltage-current characteristics [6]. We would like to stress here that the hysteresis width determines only the shielding current density which may be far below the critical value j_c.

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Earlier the existence of the universal scaling behavior for the shielding currents $j_s(H,T)/j_s(0,T)=f[H/j_s(0,T)]$ was found for $Bi_2Sr_2Ca_2Cu_3O_x$ single crystals [6] and $YBa_2Cu_3O_x$ epitaxial films [7]. The analysis of the data obtained for the $TmBa_2Cu_3O_x$ single crystal has shown, as we can see from Fig.1a, the validity of such scaling for decreasing branch of the $j_s(H)$ curve at low fields. For higher fields the deviation from this behavior exists. We have found that this part of the curve may be scaled using the relation $j_s(H,T)/j_s(H^{max},T)=\varphi(H/H^{max})$ (Fig.1b) where the maximum position $H^{max} \sim (Tc-T)^{1.14}$ has a close to linear dependence on T. Within experimental accuracy the f and φ functions are found to be independent of the magnetic field sweep rate. The presence of the two kinds of the scaling law points to two different pinning mechanisms at low and high magnetic fields.

Using the relaxation data and magnetization hysteresis curves for different magnetic field sweep rates the current voltage characteristics were extracted by the way described in Ref. [6]. Some of the results are shown in Fig.2. As in the case of $Bi_2Sr_2Ca_1Cu_2O_x$ single crystals [6] the I-V curves are close to linear in the scales logE-logj thus corresponding to the dependence $E \sim j^n$. For the fixed external magnetic field and low T, the n value decreases with the temperature increase, but at high temperatures the n(T) dependence changes to increasing one (Fig.3). For T=82K the relaxation disappears corresponding to a very sharp I-V curve with extremely large n.

At a fixed temperature, application of low magnetic field causes the n-parameter rising. However, after the sharp maximum, which may be related to the minimum of $j_s(H)$ dependence, it decreases according to the law $n \sim (H-H_0)^{-1}$ (Fig.3).

The nature of the peak-effect for HTSC is unclear yet. Several possible explanations were proposed. The widely spread model [2] is based on the suggestion that additional pinning of vortex lines may be caused by the oxygen deficient regions which become normal when the magnetic field exceeds second critical field H_{c2} of impurity phase. The supposed large dispersion in $H^i{}_{c2}$ values leads to the permanent multiplication of the pinning centers with H inducing the $j_c(H)$ increase. For high magnetic fields above H^{max} the normal regions start to intersect thus creating the paths for free flux penetration and giving rise to subdivision of the sample into the weakly coupled grains.

We have checked the granularity of the sample using the relation between shielding currents determined from the hysteresis width and the remagnetization field which is needed to invert the direction of shielding currents in the critical state [8]. Another way for the granularity check we have used is based on the measurements of the initial susceptibility χ_i during the remagnetization process [9]. For the studied orientation H∥c, the sample possesses large demagnetization which would decrease after the separation of the sample into the individual grains.

As one can see from Fig.4, almost no change in χ_i and nearly constant value of the ratio $\beta=j_s(\Delta B)/j_s(\Delta M)$ are observed for all magnetic fields $H>H^{max}$. These results show the absence of granularity for the studied sample. It is in correspondence with the conclusions of Ref. [10, 11] and differs from Ref. [2, 12]. Thus, the presence of the peak-effect for both granular and ungranular samples excludes the granularity as the origin of this behavior.

Another possible explanation of the observed behavior may be the existence of the interaction energy peak for superconducting centers [13]. This idea was extensively discussed in Ref.[14] for conventional superconductors. Similar to the Ref.[2] in this case the additional pinning may be caused by the oxygen

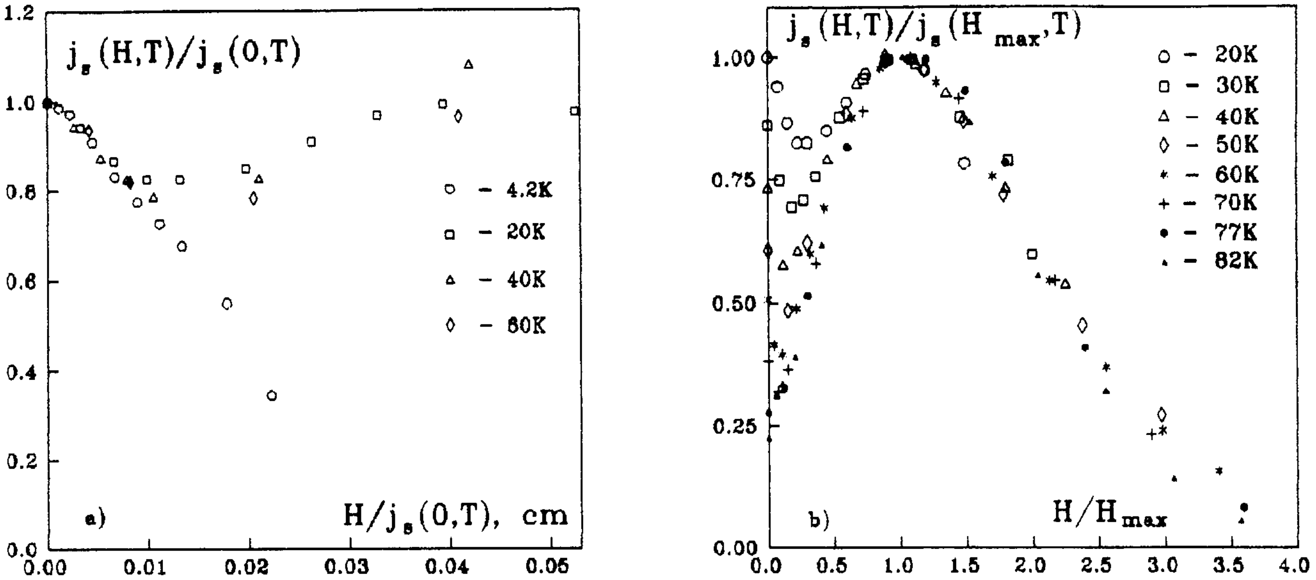

Fig.1. The scaling behavior of $j_s(H)$ dependences for low (a) and high (b) magnetic fields.

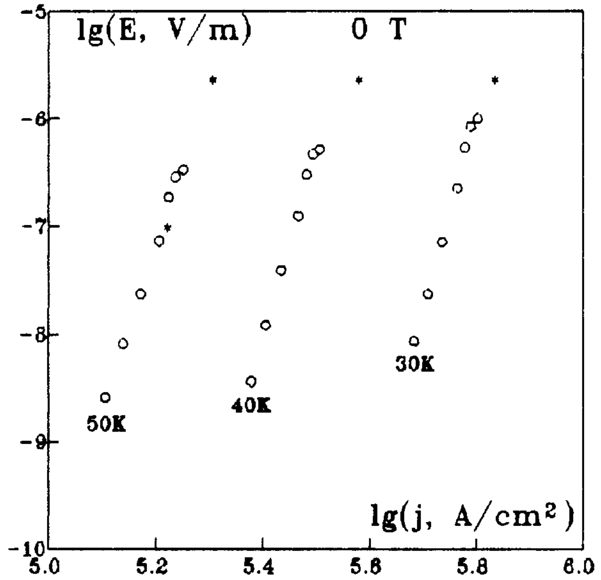

Fig.2. The voltage current characteristics for H_e=0 and different temperatures. The open circles and the stars show the data extracted from the relaxation results and magnetization hysteresis, respectively.

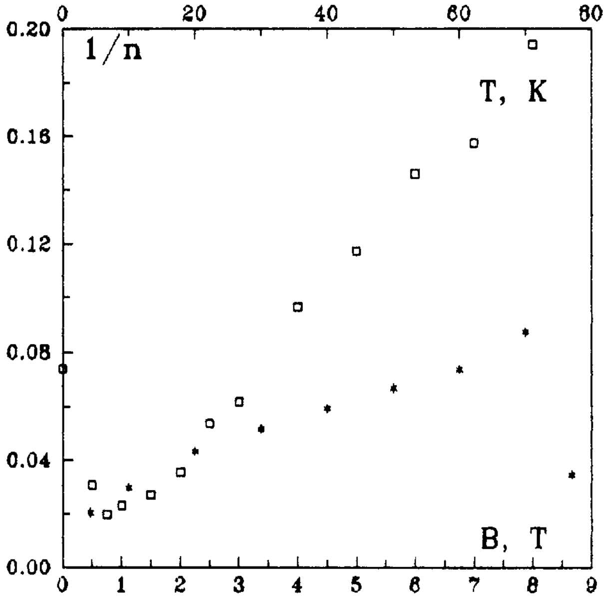

Fig.3. The dependence of the inverse n parameter on the magnetic field (squares) for T=60K and temperature (stars) for H_e=0.

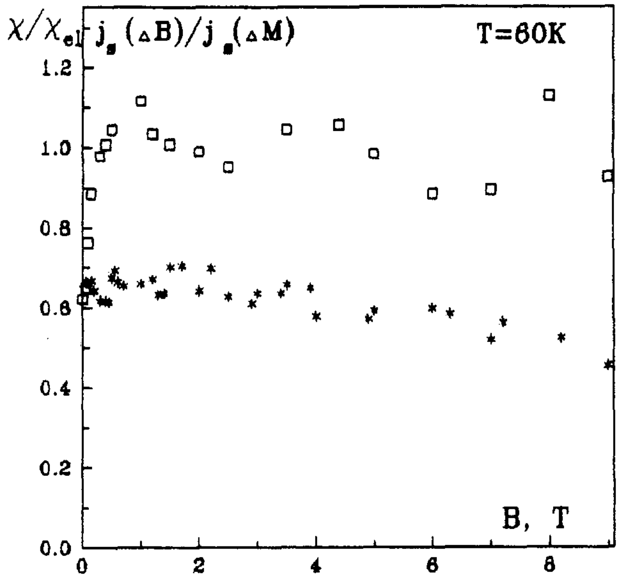

Fig.4. The magnetic field dependence of shielding current homogeneous flow criteria $j_s(\Delta B)/j_s(\Delta M)$ (squares) and normalized initial susceptibility χ_i/χ_{el} for T=60K. $\chi_{el}=1/(1-N)$ (stars) is the susceptibility for inscribed ellipsoid. H_{max} (T=60K)=23 kOe.

deficient regions. In difference with [2] the $j_s(H)$ increase behavior is not connected with the multiplication of the number of normal pinning centers, but is related to the increase of elementary pinning force of superconducting impurity center. These vortex binding forces may have two different origins. There are the magnetic interaction of the vortex with the surface of a macroscopic inclusion or the decrease of the vortex core energy E_c in the impurity region [14]. The magnetic interaction leads to the critical current proportional to the difference in reversible magnetization ΔM_{rev} between matrix and impurity phase. This difference is approximately linear on magnetic field. For the case of vortex core pinning, the binding force is determined by the difference in vortex core energy $E_c \sim H_c^2(1-B/B_{c2})$ [14] that changes also linearly with the magnetic field. The maximum pinning force in both cases corresponds to the $H^1{}_{c2}$ of impurity phase due to the ordinary suppression by magnetic field of the pinning for the normal centers. Then the unrelaxed peak position H^{max} similar to $H^1{}_{c2}$ value need to have close to linear temperature dependence near T_c.

The real situation is probably more complicated and the dispersion of $H^1{}_{c2}$ parameters also exist. Nevertheless the main observation: (i) the linear j_c increase with magnetic field, (ii) almost linear temperature shift of H^{max} position and (iii) the absence of granularity support the idea of interaction energy peak as the dominant factor for the explanation of the high field part of $j_s(H)$ dependence. The initial $j_s(H)$ decrease at low fields may be connected with the pinning by nonsuperconducting centres.

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