Физика низких температур, 1996, т. 22, № 8, с. 892–897

Anisotropy of the critical current due to twin planes and vortex melting in $YBa_2Cu_3O_{7-x}$ single crystals

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Submitted January 12, 1995

We have measured the anisotropy of the critical current due to vortex pinning by twin boundaries and compared it with calculated values. We have also investigated current-voltage characteristics, which allowed us to obtain the temperature dependences of the depinning critical current and flux flow resistance. The results are discussed within the framework of the vortex melting transition and transition from unpinned to partially pinned state of the vortex-fluid phase.

Broadening of the resistive transitions in magnetic fields is one of the distinctive peculiarities of high-T_c superconductors. Investigation of the resistive transitions of $YBa_2Cu_3O_{7-x}$ single crystals [1,2] shows that below some temperature $T_m(H)$

$$R(T) = R_0 \exp(-E/T) \tag{1}$$

with activation energy E depending on the value of magnetic field and the field vector orientation with respect to the crystallographic axes of the crystal. Above $T_m(H)$ the current-voltage characteristics are almost linear and below this temperature they are strongly nonlinear. This indicates that near $T_m(H)$ there is a transition from an unpinned vortex state at high temperatures to a pinned state of vortices at low temperatures. This transition has been interpreted to date as vortex melting near $T_m(H)$ curve [2–4], which leads to crossover from thermally activated flux flow or flux creep regime below T_m to flux flow regime above this temperature, or as a transition of vortex fluid from partially pinned to unpinned states [5,6].

In a weak pinning regime the vortex melting should remain a first order transition [7]. This is supported by the presence of temperature hysteresis on $R(T)$ curves near $T_m(H)$ in detwinned YBaCuO single crystals [4,8]. In a strong pinning regime the vortex melting is expected to be a second order transition [7]. To date there are a number of experiments that indicate strong vortex pinning by twin boundaries (TBs). The decoration experiments show higher vortex density near TBs than in the remaining volume of the superconductor [9,10]. The field-dependent magnetization shows that magnetic behavior depends on the field orientation with respect to TBs [11], and magnetic torque experiments show a fourfold increase in the pinning force when **H** is parallel to TBs [12]. A visual inspection of a spatial distribution and dynamics of the magnetic flux shows, that TB's structure of a single crystal is effective in these processes at temperatures above 20 K [13]. Vortex pinning by TBs at temperatures below T_m appears as a sharp minimum on the angular dependence of resistance near H || TB [14]. All these results show that TBs act as strong pinning centers. Therefore, a scaling description of the transition near $T_m(H)$ in the presence of TBs [15–17], which suggests the existence of a second order transition, agrees with the model of vortex line lattice melting in a strong pinning regime. On the other hand, in some twinned single crystals two separate (in temperature) phase transitions occur between low-temperature superconducting phase and high-temperature unpinned vortex fluid [6]. The higher temperature $T_m(H)$ of these two transitions was interpreted as the remnant, in the presence of pinning, of the first-order vortex-lattice melting transition that would occur in the absence of pinning. The partially pinned vortex phase that occurs below $T_m(H)$ was referred to as a «vortex slush» phase. The lower temperature was interpreted as a second order transition between the vortex-slush phase and vortex-glass phase.

Assuming TB to be a thin superconducting slab, different from and embedded in the host superconductor, strong flux pinning by TBs was found to originate from (1) an absolute minimum of the free energy when the twin boundary slab penetration length is larger than that of the host material and (2) from a surface barrier at the interface of two superconductors [18]. The model assumes that the TBs are the weak links and there are a number of experiments which support this assumption [19].

The vortex pinning by TBs theoretically was investigated by Blatter et al. [20]. Assuming the vortex line tension at TB to be smaller on ΔU than its value U in the remaining volume of superconductor, they showed, that for misorientation angles θ between **H** and TBs are greater than the critical ones:

$$\theta_{cr} = (2\Delta U/U)^{1/2}, \qquad (2)$$

the vortex line is straight and parallel to the applied magnetic field. For $|\theta| < \theta_{cr}$ the vortex line consists of alternating straight segments oriented along TBs and straight segments oriented at the angle θ_{cr} with respect to TB planes, but the average orientation of vortices coincides with the applied field. According to this model, one of the authors (SVA) calculated the angular dependence of the critical current for $|\theta| < \theta_{cr}$ and $\theta_{cr} \ll 1$ (for geometry $\mathbf{H} \perp c$, $\mathbf{I} \perp c$ and current vector oriented at the angle 45° with respect to TBs), which may be written as follows:

$$I_c(\theta) = (1+\theta)^{-1}[(|\theta|/\theta_{cr})I_c^{\perp} + (1 - |\theta|/\theta_{cr})I_c^{\parallel}]. \qquad (3)$$

Here $I_c^{\parallel}$ and $I_c^{\perp}$ are the critical currents for **H** parallel and perpendicular to TBs, respectively.

Equations (2) and (3) describe two different aspects of vortices pinning by TBs in the geometry $\mathbf{H} \perp c$, which could be called "thermodynamical" and «kinetic» pinning. The characteristic of the first one is the value of θ_{cr} that determines an equilibrium vortex structure for $|\theta| < \theta_{cr}$, since the ratio of vortex segment r aligned within TB to vortex segment s placed out of TB plane equals $r/s = (\theta_{cr}/|\theta| - 1)$ [20]. The value of $I_c(\theta)$ is determined by kinetic pinning because the Lorentz force in the geometry $\mathbf{H} \perp c$ drives vortices along TB planes and does not change their structure (the ratio r/s). Intensity of the thermodynamical pinning is proportional to the value of θ_{cr} and, according to (2), is the measure of the ratio $\Delta U/U$. Intensity of the kinetic pinning is proportional to the value of the ratio $\alpha = J_c^{\parallel}/J_c^{\perp} \approx J_c(0)/J_c(\theta_{cr})$ which, as can be shown, determines the ratio of pinning potential for thermoactivated vortex movement for **H** parallel and perpendicular to TBs. Nevertheless, both characteristics can be determined from $I_c(\theta)$ dependence.

In magnetic field we have measured resistive transitions, current-voltage and angle-voltage characteristics of $YBa_2Cu_3O_{7-x}$ single crystals containing TBs oriented in one direction only. Two crystals were picked up from the same batch processed under the same annealing regimes. The critical temperature in a zero magnetic field of the first single crystal (A) with dimensions 1.5×0.4×0.015 mm was 91.7 K and of the second one (B) with dimensions 2×0.75×0.03 mm was 92 K. The width of the resistive transitions of both crystals was about 0.3 K. Electrical resistivity of the crystals at room temperature was about 220 $\mu\Omega\cdot$cm dc-current was measured in both current directions and the voltage resolution was equal $5\cdot10^{-8}$ V. Contact resistance was less then 0.05 Ω and measurements with current values up to 30 mA without overheating of the samples were carried out. The transport current and magnetic field vectors were always applied parallel to the (a, b) plane. The current vector was parallel to direction for crystal A and to [110] for crystal B and thus it crossed TB planes in the first case and was parallel to TB planes in the second one. Deviation of the magnetic field vector from the ab plane was less than 2°. The crystals could be rotated about c axis with resolution 0.3° and the angle φ between **H** and **I** vectors could be varied from 0 up to 360°.

Figure 1 shows the resistive transitions of crystal A obtained at the current 3 mA in a zero field (curve *1*) and in the field of 15 kOe for $\mathbf{H} \parallel \mathbf{I}$ (curve *2*) and $\mathbf{H} \perp \mathbf{I}$ (curve *3*). Below $T_m \simeq 90.5$ K one can see a resistive tail on the curve *3*, that disappeared at

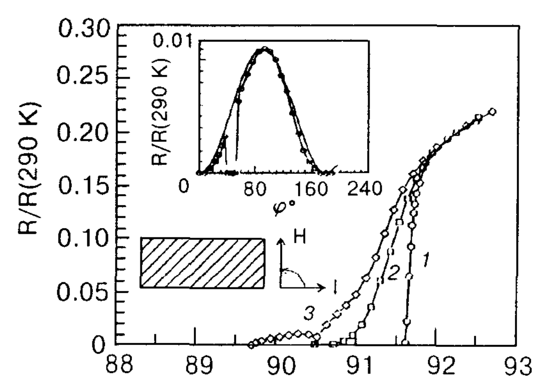

Fig. 1. Resistive transitions in zero field (curve *1*) and in the field 15 kOe for **H** ||TB (curve *2*) and for **H** ⊥ **I** (curve *3*) configurations measured with I = 3mA. The upper inset shows angular dependence of the resistance measured at temperature 90.3 K and its interpolation by Eq.4. The lower inset shows orientations of **I** and **H** vectors with respect to TBs of the sample.

transport currents less then 1 mA. One of the reasons for the tail appearance may be destruction of possible weak links at the TBs, since the transport current crossed twin planes. In this case a current of 1mA will correspond to the critical current of the TBs. But as will be shown later, the tail does not appear up to $I = 30$ mA for H || TB configuration. In addition on investigation of crystal B under the same conditions, in which transport current was parallel to TB planes, showed that the tail appeared at almost the same current density and both crystals showed the same values and temperature dependences of the depinning critical current below T_m. These facts imply that the appearance of the resistive state at high transport currents is not caused by destruction of weak links at TBs and is controlled by pinning forces only. All results described below were obtained on crystal A.

Angular dependences of the resistance at temperatures above T_m were described by the equation

$$R(\varphi) = R(\varphi = 0°) + [R(\varphi = 90°) - R(\varphi = 0°)]\sin^2\varphi, \qquad (4)$$

where the second term corresponds to the Lorentz-force-driven flux motion (as was first shown by Kwok et al. [14]). Below T_m the experimental curve $R(\varphi)$ deviates from this dependence (see upper insert in Fig.1), which is due to non-ohmic behavior at these temperatures. There is also seen a deep minimum on the $R(\varphi)$ curve, which goes to zero near $\varphi = 45°$ (H parallel to TB planes). The width of the minimum decreases with the current increase. This is seen in Fig. 2, where the voltage-angle characteristics measured with different transport current values are shown. If we define the critical current as the current at which the voltage V of 0.5 μV or 1 μV appears at the sample we can plot the $J_c(\theta)$ dependences shown in Fig. 2,*b* (curves *1* and *2*, respectively). Equation 3 determines nearly linear angular dependences of the critical current for $|\theta| << 1$. Therefore, the obtained linear experimental dependences of $I_c(\theta)$ indiicate that static kinked configuration of the vortex line is preserved in the temperature range $T < T_m$ if the vortex moves along the TBs.

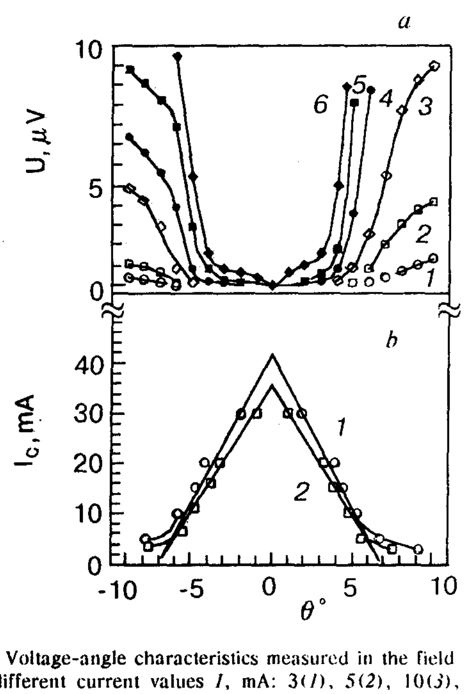

Fig. 2. Voltage-angle characteristics measured in the field 15 kOe with different current values I, mA: 3(*1*), 5(*2*), 10(*3*), 15(*4*), 20(*5*) and 30(*6*) (*a*). Angular dependences of the critical current defined at the voltage levels 1 μV (curve *1*) and 0.5 μV (curve *2*) and the extrapolation of the linear parts of the curves toward $\theta = 0$ and $I_c = 0$ (*b*).

Extrapolation of $J_c(\theta)$ curves towards $\theta = 0°$ gives the critical currents at H parallel to the TB planes which are 36 and 42 mA for $V = 0.5$ and 1 μV, respectively. The corresponding measured values of J_c at H perpendicular to TBs were 1.1 and 1.2 mA. Thus, the kinetic vortex pinning for vortex movement along c axis for H || TB geometry is about 30 times higher than its value for the vortex line oriented perpendicular to the TBs. Extrapolation of the linear segments of $J_c(\theta)$ curves towards $J_c = 0$ gives two intersection points, which limited segment $2\theta_{cr} = 14° = 0.24$ rad. One can see that the value of θ_{cr} obtained in this way does not depend within accuracy on the voltage level which J_c is defined.

Comparison of $\alpha \approx 30$ found in this work with the value $\alpha \leq 5$ found by Kwok et al. [14] shows that the kinetic pinning by TBs is much greater in our crystal. This correlates with greater values of the thermodynamical vortex pinning $\theta_{cr} \approx 7°$ compared with $\theta = 1.5°$ obtained in Ref. 14. Thus, the values of phenomenological thermodynamic and kinetic characteristics (θ_{cr} and α, respectively) of vortex pinning by TBs correlate with one another and they may have the same microscopic origin. The method of crystals growth used by us [21] is close to that described in Ref. 22. Thus, the difference in vortex pinning characteristics obtained by us and in Ref. 14 may be due to thermal treatment of the samples and (or) to differences in the distance between TB planes and impurities contained in compounds used for the crystals growth.

Curve *1* in Fig.3 represents the angular dependence of the resistance measured at transport current value 30 mA. The curve is quite different from the one obtained in [23, Fig. 15]: the obtained $R(\theta)$ dependence has a positive curvature, in contrast to the depen-

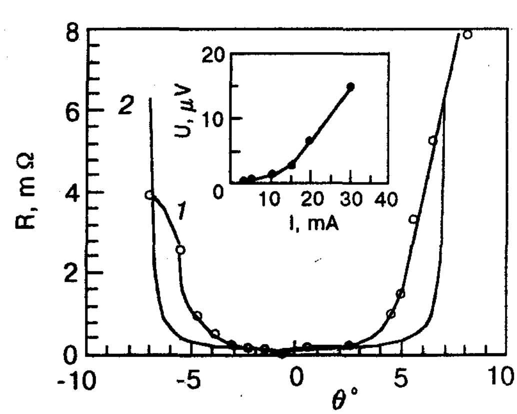

Fig. 3. Angular dependence of the resistance measured at transport current $I = 30$ mA and the dependence given by Eq.5 (upper and lower curves, respectively). Inset shows current-voltage characteristics measured for $\theta \simeq 3°$.

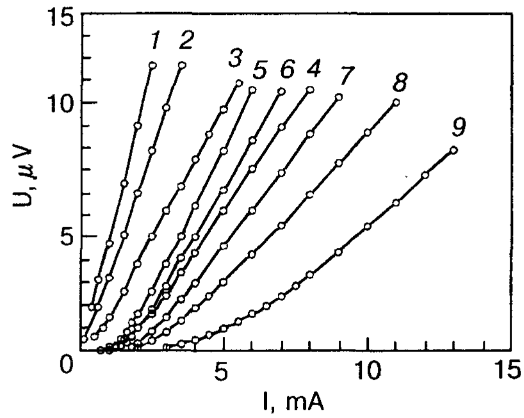

Fig. 4. Current-voltage characteristics measured in the field 15 kOe for H ⊥ I geometry at different temperatures *T*, K: 90.94 (*1*);, 90.8 (*2*); 90.61 (*3*); 90.49 (*4*); 90.26 (*5*); 90.03 (*6*); 89,8 (*7*); 89,68 (*8*); 89,5 (*9*).

dence obtained in Ref. 23, which has a negative curvature. Flesher et al. [23] presented the formula for angular dependence of the resistance

$$\rho(\theta) = \rho_{TB}(r + s)/[r + (\rho_{TB}/\rho_b)s], \qquad (5)$$

where ρ_{TB} is the resistivity associated with the flux motion in the TB's and ρ_b is the corresponding resistivity for flux motion in the bulk when $\theta = \theta_{cr}$. Curve *2* in Fig. 3 was obtained from this expression with experimental values $R_{TB} = 1.6 \cdot 10^{-4}$ Ohm and $R_b = 4 \cdot 10^{-2}$ Ohm. Although both the experimental dependence and the curve given by Eq.5 have positive curvature, the fit of the data is poor. It should be noted that Eq.5 is correct for the linear regime. But, as it is seen in inset of Fig.3, current-voltage characteristics at temperatures $T < T_m$ are nonlinear and hence Eq.5 is not correct in this temperature range. On the other hand, at temperatures $T \geq T_m(H)$ we have observed angular dependences of the resistance similar (having a negative curvature) to that reported in Ref.24. But $R(\theta)$ is very sensitive to misorientation in this temperature region between vector **H** and *ab* plane, and the question whether the static configuration of kinked structure of vortices is preserved in the high-temperature regime ($T \geq T_m$) needs more detailed investigations. Such experiments now are in progress.

Figure 4 shows current-voltage characteristics measured in the field 1.5 T for **H** ⊥ **J** configuration. As is seen, at temperatures above 90.5 K the curves are almost linear. Below 90.5 K the initial parts of *I–V* curves are strongly nonlinear, but they become linear at high current densities. The transition from nearly ohmic to strongly nonohmic behavior near T_m indicates the transition from unpinned state of vortices above T_m to pinned state below T_m. Therefore, in the temperature range $T > T_m$ the measured dependence $R(T)$ shown in Fig. 1 corresponds to the temperature dependence of the flux flow resistance R_{fl}. Below T_m the linear parts of *I–V* curves observed at high current densities may correspond to the flux flow regime when the Lorentz force is greater than the pinning force $F_p = J_{cd}B$, which is defined by the depinning critical current I_{cd}. In this case extrapolation of linear parts of the curves to zero voltage gives the depinning critical current values and the derivative dV/dJ defines the flux flow resistance R_{fl}. It should be noted, that the *I–V* curves below T_m were linear up to $I = 30$ mA. For the currents above 30 mA deviation from linearity was observed which may be due to resistive overheating of the sample.

Curve 1 in Fig. 5 shows the obtained temperature dependence of R_{fl} and its interpolation (dashed curve) by the Bardeen-Stephen formula [24]

$$R_{fl} = R_N B / B_{c2}. \qquad (6)$$

The dependence $R_N(T)$ was defined as extrapolation of the temperature-linear normal state resistance. The best fit of the experimental data with Bardeen–Stephen model was obtained for $dB_{c2}/dT \simeq 11T/K$ (this value is in good agreement with data obtained in Ref.25). It is seen that experimental data in the narrow temperature interval ($\Delta T \simeq 0.5$ K) near T_m deviates from the dependence given by Eq. 6. This probably means that in this temperature region at transport currents $I < 30$ mA only part of vortices moves under the current-induced stresses and some

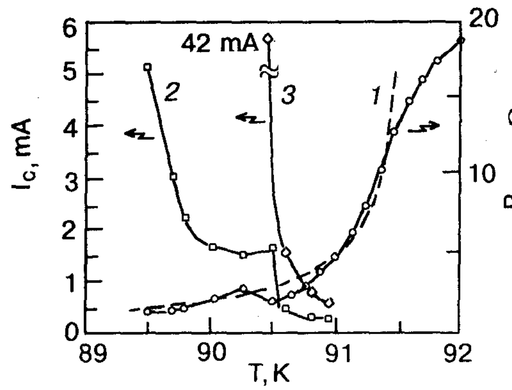

Рис. 5. Temperature dependences of the flux flow resistance (curve 1) and depinning critical currents measured for H ⊥ I (curve *2*) and H ∥ TB (curve *3*) geometry.

part of them remains in a pinned state. We have observed [26] similar behavior over a rather broad temperature interval ($\Delta T \simeq 6$ K) for other experimental conditions (H ∥ c, I ⊥ c, I ⊥ TBs). The result was interpreted as a plastic flow of vortex lattice (caused by high current-induced shear stresses) placed between TBs with respect to strongly pinned vortices placed near TBs. The main argument supporting this viewpoint was the good agreement of the experimental $I_c(T)$ dependence with the theoretical one predicted for shear limited critical current.In the considered geometry of the experiment the effect occurs in a very narrow temperature region and we had no possibility of checking the validity of this mechanism of vortex flow.

Temperature dependences of the depinning critical current obtained for **H** ⊥ **I** and **H** ∥ TBs geometry are presented in Fig. 5 by curves *2* and *3*, respectively. In both cases I_{cd} increases very rapidly near $T_m = 90.5$ K over a rather narrow temperature interval $\Delta T \approx 0.2$ K. The most drastic increase in the critical current below T_m is observed for H ∥ TB (see curve *2* in Fig. 4). The point 42 mA was obtained by linear extrapolation of the $I_c(\theta)$ dependence to $\theta = 0$ and it defines the critical current for the voltage criterion of 1 μV. Therefore, the depinning critical current is even higher than 42 mA. The increase in J_{cd} (below T_m for **H** ∥ TB configuration) by more than 40 times is not surprising, since, as is seen in Fig. 2,*b*, the strongest vortex pinning at $T < T_m$ is realized for H ∥ TB. Above T_m vortices are in a melted, unpinned state, and they could easily move as the Lorentz force arises. The average distance between TBs in our crystals, measured by electron and polarized light microscopy, is about 4 μm. In magnetic field 1.5 T the distance between vortices is much smaller (about 400 Å). Therefore, even if one supposes that vortices aligned within TBs are strongly pinned, there are a large number of vortices which could easily move under the Lorentz force action, since the shear modulus of the unpinned liquid phase is zero. We have observed a narrow minimum on $R(\varphi)$ curves near $\varphi = 45°$ above 90.5 K, but its depth was less than 5 percents and was independent on the current value. This means that vortices (or some part of them) aligned within TBs probably are pinned by TBs above T_m, but this question needs more detailed investigations.

We have measured the resistive transition curves both in heating and cooling regimes of the sample in magnetic fields up to 6 T for **H** ∥ **c** and **H** ⊥ **c** configurations. The transport current was *50 μA* and the rate of cooling and heating varied from 0.1 to 4 K/*h*. No temperature hysteresis near T_m was observed, with an experimental accuracy of 3 mK. For comparison, the measurement of the resistive transition of the detwinned single crystal [4] in a magnetic field 6 T (H ∥ c configuration) with the transport current 20 μA shows the temperature hysteresis to be about 25 mK. From the view-point of vortex melting near T_m this probably means that vortex melting in crystals containing such strong pinning centers as TBs is a second order transition.

Another possibility of the change of the vortex dynamics near T_m can arise from the existence of two different vortex-liquid phases above and below T_m in weak pinning regime [5] or from the appearance of a vortex-slush phase below T_m in samples with intermediate disorder [6]. Both these models predict that above T_m disorder does not affect the vortex movement and the linear resistance R_l equals R_{fl}, but below T_m the vortex-slush or vortex-liquid phases are partially pinned with $R_l \ll R_{fl}$, and R_l decreases exponentially with increase in temperature. As was shown above, in our crystals TBs act as strong pinning centers and the sample behavior should be closer to the model with the intermediate disorder. Although we have not observed the linear resistance at small currents below T_m (this may be due to the very small values of R_l and the resolution of our equipment), the presence of a plateau on $I_{cd}(T)$ dependence in the temperature interval $\Delta T \simeq 0.7$ K just below T_m may be due to the existence of the vortex slush phase at these temperatures, below which a true superconducting phase exists and the depinning critical current rapidly increases with decrease in temperature.

In summary, we have obtained good agreement between the experimental and theoretical angular dependences of the critical current due to vortex pinning by TBs. Comparison of obtained thermodynamical and kinetic vortex pinning characteristics with literature data reveals the correlation between them. We have obtained temperature dependences of the depinning critical current and flux flow resistance. The depinning critical current increases jumpwise near T_m. Below T_m a narrow plateau on $I_{cd}(T)$ dependence is observed with subsequent rapid increase in the critical current.

The reported results are the first step of our resistive investigations of vortex pinning in YBaCuO single crystals having unidirectional twins. The work was suppoted by the State Program on superconductivity (project «Pinning») and was supported in part by International Soros Science Foundation (grant No PSU 052103).

1. T. T. M. Palstra, B. Batlogg, R. B. van Dover, L. F. Schneemeyer, and J. V. Waszczak, *Phys. Rev.* **B41**, 6621 (1990).
2. W. K. Kwok, S. Fleshler, U. Velp, V. M. Vinokur, J. Downey, and G. W. Crabtree, *Phys. Rev. Lett.* 69, 3370 (1992).
3. M. Charalambous, J. Chaussy, and P. Lejay, *Phys. Rev.* B45, 5091 (1992).
4. H. Safar, P. L. Gammel, D. A. Huse, D. J. Bishop, J. P. Rice, and D. M. Ginzberg, *Phys. Rev. Lett.* 69, 824 (1992).
5. V. M. Vinokur, V. B. Geshkenbein, A. I. Larkin, and M. V. Feigelman, *Zh. Eksp. Teor. Fiz.* **100**, 1104 (1991) [*Sov. Phys. JETP* 73, 610 (1991)].
6. T. K. Wortington, M. P. A. Fisher, D. A. Huse, John Toner, A. D. Marwick, T. Zabel, C. A. Feild, and F. Holtzberg, *Phys. Rev.* B46, 11854 (1992).
7. D. S. Fisher, M. P. A. Fisher, and D. A. Huse, *Phys. Rev.* B43, 130 (1991).
8. W. K. Kwok, J. Fendrich, S. Flesher, U. Welp, J. Downey, G. W. Crabtree, and J. Giapintzakis, *Physica* B197, 579 (1994).
9. L. Ya. Vinnikov, L. A. Gurevich, G. A. Emelchenko, and Yu. A. Osipyan, *Solid State Commun.* 67, 421 (1988).
10. G. J. Dolan, G. V. Chandrashekhar, T. R. Dinger, C. Field, and F. Holtzberg, *Phys. Rev. Lett.* 62, 827 (1990).
11. L. J. Swartzendruber, A. Roitburg, D. L. Kaiser, F. W. Gayle, and L. H. Bennett, *Phys. Rev. Lett.* 64, 483 (1990).
12. E. M. Georgy, R. B. van Dover, L. F. Schneemeyer, A. E. White, and H. M. O'Bryan, *Appl. Phys. Lett.* 56, 2465 (1990).
13. A. I. Belyaeva, S. V. Voijtsenya, V. P. Yuriyev, M. A. Obolenskii, and A. V. Bondarenko, *Solid State Commun.* 856, 427 (1993).
14. W. K. Kwok, U. Velp, G. W. Grabtree, K. G. Vandervoort, R. Hulscher, and J. Z. Liu, *Phys. Rev. Lett.* **64**, 966 (1990).
15. M. B. Salamon, J. Shi, N. Overend, and M. A. Howson, *Phys. Rev.* B47, 5520 (1993).
16. N.-C. Yeh, W. Jiang, D. S. Reed, U. Kriplani, and F. Holtzberg, *Phys. Rev.* B47, 6146 (1993).
17. D. S. Reed, N.-C. Yeh, W: Jiang, U. Kriplani, and F. Holtzberg, *Phys. Rev.* B47, 6150 (1993).
18. R. E. Hetzel, A. Sudbo, and D. A. Huse, *Phys. Rev. Lett.* 69, 518 (1992).
19. *Physical Properties of High Temperature Superconductors*, D. M. Ginzberg (ed.), World Scientific (1990).
20. G. Blatter, J. Rhyner, and V. M. Vinokur, *Phys. Rev.* B43, 7826 (1991).
21. M. A. Obolenskii, A. V. Bondarenko, V. I. Beletskii, V. N. Morgun, V. P. Popov, N. N. Chebotaev, A. S. Panfilov, A. I. Smirnov, O. A. Mironov, S. V. Chistyakov, and I. Yu. Skrilev, *Fiz. Nizk. Temp.* 16, 110 (1990) [*Sov. Low Temp. Phys.* 16, 639 (1990)].
22. D. L. Kaiser, F. Holtzberg, M. F. Chisholm, and T. K. Wortington, *J. Cryst. Growth* 85, 593 (1987).
23. S. Flesher, W. K. Kwok, U. Welp, V. M. Vinokur, M. K. Smith, J. Downey, and G. W.Grabtree, *Phys. Rev.* B47, 14448 (1993).
24. J. Bardeen and M. J. Stephen, *Phys. Rev.* A140, 1179 (1965).
25. V. Welp, W. K. Kwok, G. W. Grabtree, K. Vandervoort, and J. Z. Ciu, *Phys. Rev. Lett.* 62 , 1908 (1989).
26. A. V. Bondarenko, M. A. Obolenskii, R. V. Vovk, A. V. Samoylov, V. A. Shklovskij, and A. G. Sivakov, *Proc. of the 7th IWCC on the Critical Currents in Superconductors*, Alpbach, Austria, 24-27 Jan.(1994).