

Structure lamination influence on the magnetic flux dynamics in $YBa_2Cu_3O_{7-\delta}$ single crystals

D.A.Lotnik, A.V.Sokolov, R.V.Vovk

Kharkiv National University, 4 Svoboda Sq., 61022 Kharkiv, Ukraine

Received August 7, 2014

Dynamics of the vortex matter in $YBa_2Cu_3O_{7-\delta}$ single crystal with unidirectional twin boundaries was studied experimentally in a wide range of velocities of the magnetic flux in the tilted magnetic field. It was determined that with orientation of the magnetic field vector in the locality of *ab*-plane, the dynamics of the magnetic flux near the melting temperature of the vortex lattice can be described by the Kim-Anderson model and under temperature lowering — by the theory of collective pinning on small-scale defects or by the vortex glass model. The intrinsic pinning caused by the layered crystal structure of the material has an impact on the dynamics of magnetic flux and this effect increases with the temperature decreasing.

Динамика вихревой материи монокристалла $YBa_2Cu_3O_{7-\delta}$ с однонаправленной системой двойниковых границ экспериментально изучена в широком диапазоне скоростей движения магнитного потока в наклонных магнитных полях. Показано, что при ориентации вектора магнитного поля в окрестности *ab*-плоскости динамика магнитного потока вблизи температуры плавления вихревой решетки может быть описана теорией Андерсона-Кима, а с понижением температуры — теорией коллективного пиннинга на мелкомасштабных дефектах или моделью вихревого стекла. Собственный пиннинг, обусловленный слоистой кристаллической структурой материала, оказывает влияние на динамику магнитного потока, и это влияние возрастает по мере понижения температуры.

Вплив шаруватості структури на динаміку магнітного потоку в монокристалах $YBa_2Cu_3O_{7-\delta}$. ***Д.О.Лотник, О.М.Соколов, Р.В.Вовк.***

Динаміку вихорової матерії монокристала $YBa_2Cu_3O_{7-\delta}$ з односпрямованою системою двійникових меж експериментально вивчено у широкому діапазоні швидкостей руху магнітного потоку в похилих магнітних полях. Показано, що при орієнтації вектора магнітного поля поблизу *ab*-площини динаміка магнітного потоку біля температури плавління вихорової решітки може бути описана теорією Андерсона-Кіма, а при зниженні температури) теорією колективного пінінгу на дрібномасштабних дефектах або моделлю вихорового скла. Власний пінінг, обумовлений шаруватою кристалічною структурою матеріалу, впливає на динаміку магнітного потоку, і цей вплив зростає в міру зниження температури.

1. Introduction

The structural anisotropy presence in high temperature cuprate superconductors (HTSC) significantly affects their physical properties [1–3]. However, due to an existence of cuprate layers some of these properties cannot be correlated with the simple 3D-anisotropy. This is not a unique feature of the HTSC, but is also a characteristic feature of the traditional (so-called "cold") superconducting materials [4, 5]. The layered structure also leads to some interesting features of the electromagnetic characteristics of these compounds. For example, at a certain temperature T^* the 2D-3D transition is observed [6, 7], wherein the coherence length ξ_c along c-axis becomes shorter than the distance between CuO_2 layers. Also, at low temperatures in the magnetic field ($H > H_{c1}$) applied along the layers, the vortices can be — energetically favorable — located between the two CuO_2 layers. As stated in [8], in tilted magnetic field, the vortices are locked in ab-plane if an angle of the slope of the magnetic field is less than a certain critical angle ($\theta < \theta_c$). An experimental implementation of this regime has been confirmed in $Tl_2Ba_2Cu_2O_8$ and $Bi_2Sr_2CaCu_2O_8$ compounds [9, 10]. In $YBa_2Cu_3O_{7-\delta}$ single crystals such studies are usually complicated by the presence of twin boundaries (TB). These, in turn, are powerful pinning centers [11–14] and an additional source of the anisotropy [15]. In this work we study an influence of the layering structure on its intrinsic pinning and on dynamics of the magnetic flux of the vortex system in $YBa_2Cu_3O_{7-\delta}$ single crystals with a given orientation of TB, at which an impact on the scattering of normal carriers of the transport current is minimized.

2. Experimental

$YBa_2Cu_3O_{7-\delta}$ single crystals were grown by the solution-melt technology in a gold crucible according to [7, 15]. With oxygen saturation in the $YBa_2Cu_3O_{7-\delta}$ compounds a tetra-ortho structural transition occurs, which leads to the twinning of the crystal in order to minimize its elastic energy. For resistivity studies the thin crystals were selected with penetrating the TB and with unidirectional areas of dimensions 0.5×0.5 mm^2. This allowed to cut out bridges with unidirectional TBs and with a width of 0.2 mm, and with a distance between the potential contacts of 0.3 mm. The twin boundaries inside the bridge were oriented in one direction. Herewith, the bridge was cut in such a way that the transport current vector $\mathbf{I_{ab}}$ was parallel to the planes of the TB, which minimizes their impact on the scattering of normal carriers of the transport current. Electric contacts were formed by applying silver paste onto the crystal surface, followed by the connection of silver conductors and three hour annealing at 200°C in oxygen atmosphere. Conductors for the current contacts were made using foil with thickness of 0.1 mm and width of 2 mm and for the potential contacts we used conductors with diameter 0.05 mm. This method allowed us to obtain the low transient resistance in the electrical contacts and to perform resistive measurements at transport currents up to 1 A without overheating the contacts.

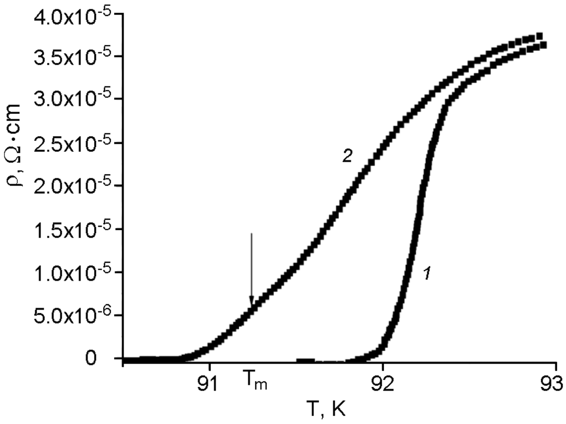

Fig. 1. Resistive transitions to the superconducting state under $H = 0$ and $H = 12.7$ kOe (curves *1* and *2*, respectively). Arrow indicates the T_M temperature.

The capacitance voltage characteristics (CVC) and the resistivity measurements were carried out at the constant current. The magnetic field up to 12.7 kOe was created by an electromagnet. Rotation of the magnet could change the orientation of the field relative to the crystal. The magnetic field orientation accuracy was 0.2°. The bridge was mounted in the measuring cell in such a way that vector **H** is always perpendicular to the transport current vector **j**. Temperature was measured by a platinum thermistor and voltage measurements were performed by using B2-38 nanovoltmeter. The temperature measurement accuracy was 0.005 K and the temperature stability during CVC measurements was no less than 0.01 K.

3. Results and discussion

Fig. 1 shows the resistive transition to the superconducting state of $YBa_2Cu_3O_{7-\delta}$ single crystal measured at zero magnetic field and at the field of $H = 12.7$ kOe. The magnetic field vector is oriented parallel to ab-plane of the crystal. The critical temperature of the crystal was $T_c = 92.3$ K, and width of the resistive transition was $\delta T_c \approx 0.3$ K. These values indicate the high quality of the crystals, as well as that the oxygen deficiency δ does not exceed 0.07 [7, 16]. The resistive transition in the magnetic field is substantially broadened. The temperature T_M, associated with the vortex lat-

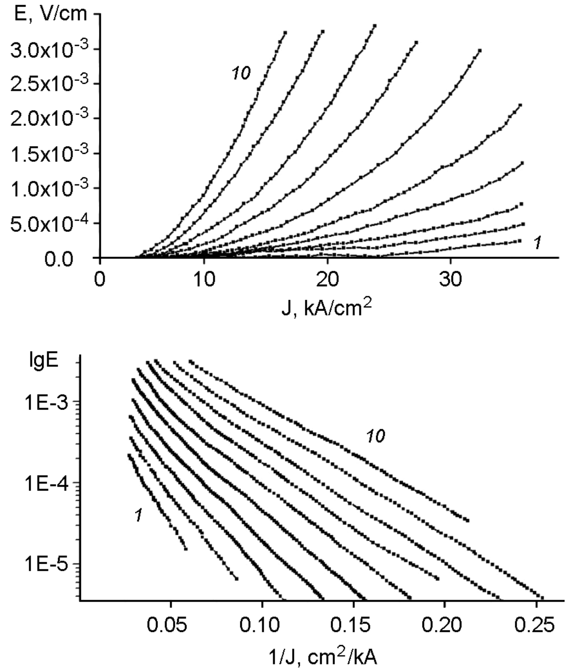

Fig. 2. CVC of YBaCuO single crystal measured at T, K: 80; 81.38; 81.97; 82.55; 83.09; 83.71; 84.3; 84.85; 85.45 and 86.01 (curves *1–10*, respectively) with the vector $\mathbf{H}\|ab$-plane.

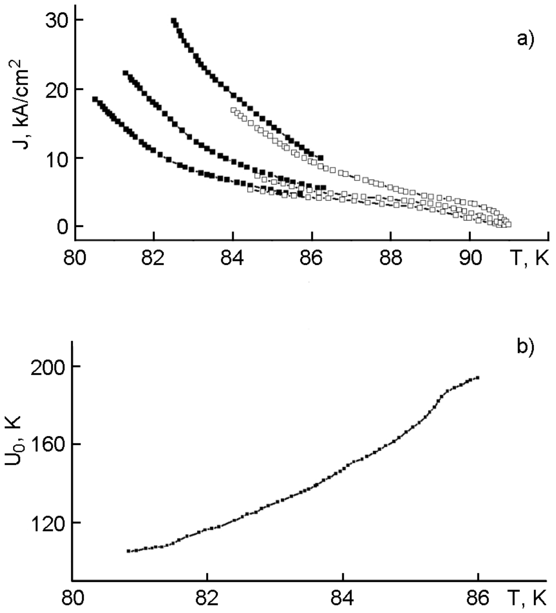

Fig. 3. Temperature dependences of the critical current (a) and of pinning potential (b).

tice melting was determined by the low temperature peak of the derivative $d\rho(T)/dT$ [17] (the peak is shown with an arrow in the figure). It is believed that at $T > T_M$, the vortex liquid phase is in the non-pinning state [11–14, 17].

Measurements of the capacitance voltage characteristics at $T > T_M$ show, that in this temperature range, the CVC are linear, that is the vortex system is definitely in the non-pinning state [11–14]. At temperatures below T_M, the CVC are basically non-linear as it can be seen from Fig. 2(a). As it is established in [12], the initial nonlinearity sections of the curves is due to the thermally activated "flux creep", which occurs when the Lorentz force $F_L = IB$ (where B is the magnetic induction vector) is less than the pinning force $F_P = I_d B$, which, in its turn, is determined by the depinning critical current I_d.

Fig. 2(b) shows the same characteristics in $\log E$—J^{-1} coordinates. It is seen that the initial sections of the experimental curves are linear in these coordinates. This suggests that in accordance to [11, 12] the vortex dynamics could be well described by the theory of collective pinning model in the small-scale defects or by the vortex glass model.

Unfortunately, in our experiments the regime of viscous flow of the magnetic flux was not reached and therefore we were not able to determine the depinning critical current by extrapolating the linear portion of the CVC to the point of intersection with the horizontal axis (dynamic method) [11]. Therefore, to set up the critical current we choose the method of determination by the electric field intensity on a specimen E, equal to 10^{-5}, 10^{-4} and 10^{-3} V/cm, respectively (statistical method) [12]. The temperature dependence of the critical current, corresponding to these values is shown in Fig. 3(a) by the shaded symbols. Presenting to the equation

$$E = E_0\exp[U/T(1 - J_c/J)] \qquad (1)$$

value of the critical current J_c defined in terms of the electric field intensity on the sample we determined the temperature dependence of the pinning potential $U(T)$. Here, U is the pinning potential, and E_0 is a phenomenological parameter, the physical interpretation of which depends on the model. The temperature dependence of the pinning potential, as defined in the framework of the collective pinning (or vortex glass) model, regarding the criterion for determining the critical current $E = 10^{-4}$ V/cm is shown in Fig. 3(b). It can be seen that the pinning potential decreases when the temperature is decreasing. Notably, the absolute values

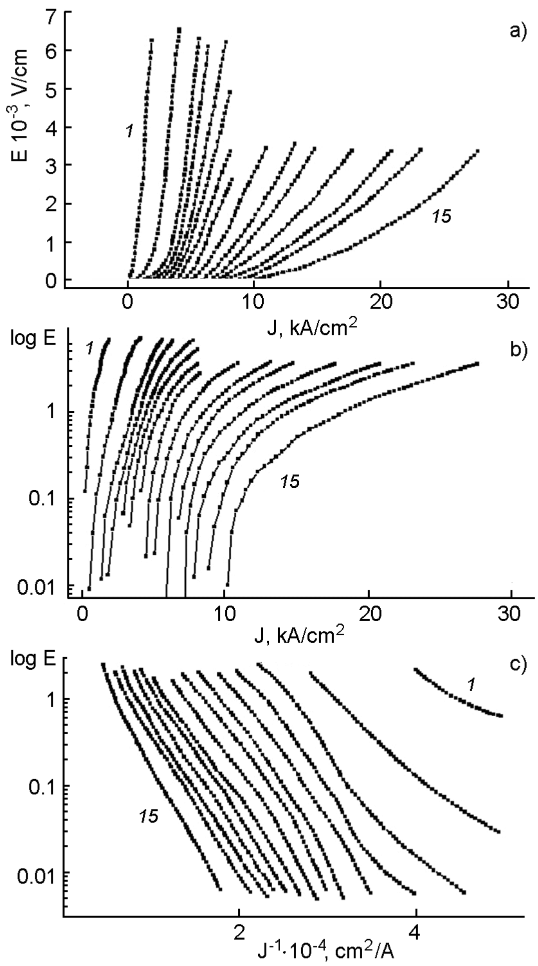

Fig. 4. CVC for YBaCuO single crystal, measured at T, K: 90.94; 90.55; 89.99; 89.45; 88.94; 88.43; 87.95; 87.56; 87.02, 864; 86.06; 85.49; 84.93; 84.59 and 83.86 (curves *1–15*, respectively) at disorientation angle β between $\boldsymbol{H}$ and *ab*-plane equal to 3°.

$U_0 \approx 200$ K obtained are about an order of magnitude lower than the values obtained within the Kim-Anderson model [18].

We have also measured the CVC at the disorientation angle β of the magnetic field vector relative to *ab*-plane (β = 3°). According to [12, 17] for this geometry, an influence of the intrinsic pinning on the dynamics of the magnetic flux is excluded. The results are shown in Fig. 4a. As it can be seen from the figure the CVC form is changing under the temperature decreasing. The slope of the curves decreases and their density changes at a fixed level of tension in the entire range of currents. Fig. 4b shows the same characteristics in logarithmic coordinates. We can see that near TM the initial sections of the characteristics are straightened. As the temperature decreases the CVC are worse described by the Kim-Anderson model [18]. Fig. 4c shows the same characteristics in $\log E$—J^{-1} coordinates. It can be seen that at low temperatures the CVC are satisfactorily described by the equation predicted in the theory of collective pinning model in the small-scale defects (or vortex glass model) [17]. Using the above criteria to determine the critical current, we obtained the curves shown in Fig. 3a with the hollow symbols. The figure shows that the dependence of $J_c(T)$ has the so called *s*-shaped form that is rather sharply increasing at temperatures below T = 86.5 K. Herewith, the difference in the magnitude of the critical current in the field with $\mathbf{H}\|ab$-planes of the crystal compared to the values of the critical current in field inclined at the angle (at the same temperature intervals) increasing with the increasing levels of E, by which the value of J_c was determined. Notably, as the temperature decreases, the difference increased, which in turn indicates the increase of the intrinsic pinning contribution. In this, the possible strengthening of the role of some specific mechanisms of the quasi-particle interaction could play a significant role [19–25].

4. Conclusion

To conclude the experimental results we would like to mention that when the orientation of the magnetic field vector is in the locality of *ab*-plane, the dynamics of magnetic flux near the melting point of the vortex lattice can be well described by the Kim-Anderson model and when the temperature is lowered — by the collective pinning (or vortex glass) model. The intrinsic pinning caused by the layered crystal structure of the material has a significant impact on the dynamics of the magnetic flux that increases by decrease of the temperature.

References

1. A.A.Abrikosov, *Usp.Fiz.Nauk*, **168**, 683 (1998).
2. A.Chroneos, I.L.Goulatis, R.V.Vovk, *Acta Chim. Slovenica*, **54**, 179 (2007).
3. R.V.Vovk, N.R.Vovk, O.V.Shekhovtsov et al., *Supercond.Sci.Technol.*, **26**, 085017 (2013).
4. R.A.Klemm, A.Luther, M.R.Beasley, *Phys. Rev.B*, **12**, 877 (1975).
5. V.V.Schmidt, The Physics of Superconductors, Springer-Verlag, Berlin-Heidelberg (1997).
6. L.G.Aslamazov, A.I.Larkin, *Phys.Lett.*, **26A**, 238 (1968).

7. M.A.Obolenskii, R.V.Vovk, A.V.Bondarenko, N.N.Chebotaev, *Low Temper. Phys.*, **32**, 571 (2006).
8. D.Feinberg, C.Villard, *Phys. Rev. Lett.*, **65**, 919 (1990).
9. D.H.Chung, M.Charparale, M.J.Naughton, in: Proc. VIth Conference on Superconductivity, September 1992, Buffalo (AIP), New York (1993).
10. J.C.Martinez et al., *Phys. Rev. Lett.*, **69**, 2276 (1992).
11. A.V.Bondarenko, V.A.Shklovskij, M.A.Obolenskii et al, *Phys. Rev. B*, **58**, 2445 (1998).
12. A.V.Bondarenko, A.A.Prodan, M.A.Obolenskii et al., *Low Temper. Phys.*, **27**, 339 (2001).
13. A.V.Bondarenko, A.A.Prodan, M.A.Obolenskii et al., *Physica C*, **317–318**, 655 (1999).
14. W.K.Kwok et al., *Phys. Rev. Lett.*, **69**, 3370 (1992).
15. R.V.Vovk, M.A.Obolenskii, Z.F.Nazyrov et al., *J. Mater. Sci.: Mater. Electron.*, **23**, 1255 (2012).
16. P.Schleger et al., *Physica C*, **176**, 261 (1991).
17. R.V.Vovk, Z.F.Nazyrov, M.A.Obolenskii, *J. Alloys and Comp.*, **509**, 4553 (2011).
18. P.W.Anderson, Y.B.Kim, *Rev. Mod.*, **36**, 39 (1964).
19. R.V.Vovk, C.D.H.Williams, A.F.G.Wyatt, *Phys. Rev. B*, **69**, 144524 (2004).
20. R.V.Vovk, A.A.Zavgorodniy, M.A.Obolenskii et al., *J. Mater. Sci.: Mater. Electron*, **22**, 20 (2011).
21. D.H.S.Smith, R.V.Vovk, C.D.H.Williams, A.F.G.Wyatt, *New J. Phys.*, **8**, 128 (2006).
22. M.A.Obolenskii, A.V.Bondarenko, R.V.Vovk et al., *Low Temper. Phys.*, **23**, 882 (1997).
23. R.V.Vovk, A.A.Zavgorodniy, M.A.Obolenskii et al., *Modern Phys. Lett. B*, **24**, 2295 (2010).
24. R.V.Vovk, M.A.Obolenskii, A.A.Zavgorodniy et al., *J. Mater. Sci.:Mater. Electron.*, **20**, 858 (2009).
25. R.V.Vovk, G.Ya.Khadzhai, Z.F.Nazyrov et al., *Physica B*, **407**, 4470 (2012).