ON MAGNETIC PHASE DIAGRAM OF $YBA_2Cu_3O_7$ IN MAGNETIC FIELDS UP TO 500 T

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Magnetic phase diagram of high temperature superconductors (HTSC) in ultrahigh magnetic field is one of fundamental problems of HTSC physics. Knowledge of the upper critical field (H_{C2}) is of importance for thermodynamic description of a superconducting state. The dependence $H_{C2}(T)$ at low temperatures can provide clues to understanding of the microscopic mechanism of HTSC. For HTSC the $H_{C2}(T)$ is well known near the critical temperature (T_C) only. Thus measurements of onset of diamagnetism in $YBa_2Cu_3O_7$ (YBCO) singlecrystal performed near T_C [1] yield the following values $\left(\frac{dH^{\parallel}_{C2}(T)}{dT}\right)_{T_C}$ =-1,9 T/K and $\left(\frac{dH^{\perp}_{C2}(T)}{dT}\right)_{T_C}$ =-10,5 T/K, where $\parallel$ and $\perp$ denote that the crystallographic axis $\bar{c}$ is directed along and perpendicular to the magnetic field respectively. According to MWHH theory [2] the orbital limiting value of the upper critical magnetic field at absolute zero has the form

$$H_{C2}(0) = -0.7 \cdot T_C \left(\frac{dH_{C2}(T)}{dT}\right)_{T_C} . \tag{1}$$

From here we obtain the estimations $H^{\parallel}_{C2}(0) = 122$ T and $H^{\perp}_{C2}(0) = 675$ T, for T_C=92 K.

Magnetic hysteresis of YBCO single crystal was investigated in pulsed magnetic field in [3]. Following irreversibility fields were obtained there: $H^{\parallel}_R(0) \approx 40$ T and $H^{\perp}_R(0) \approx 110$ T. It was argued [3] to be possible to identify the irreversibility line with $H_{c2}(T)$ at low temperatures. However, these values seem to be too low if we take into account the MWHH estimation presented above and a set of experimental investigations of ceramic [4,5] and film [6-8] samples of YBCO.

In this paper, in section 1, recent results of a research of YBCO thin films by means of microwaves in magnetic field up to 500 T [9,10] is discussed; in section 2, magnetic phase diagram of YBCO is built, and it is shown that the divergences between different methods of H_{C2} measurement is due to a transition from vortex glass to vortex lattice: in section 3, dependence of anisotropy of H_{C2} on temperature is discussed.

1. Measurement of complex conductivity of YBCO thin films in ultrahigh magnetic field

To produce the ultrahigh magnetic fields we used explosive-driven flux compression generators. The fields up to 150 T were gained from two-stage generator [11], and fields up to and above 500 T were obtained from magnetocumulative generator MC-1 [12].

A measurement unit comprised a foam-plastic cryostat into which a YBCO film was inserted. The samples were cooled by flowing liquid helium or helium gas. Temperature were measured by two calibrated thermodiodes glued on “cold” walls of a helium channel before and after the sample. Typical accuracy of temperature measurement was within 1 K. The magnetic field were measured by inductive and magnetooptic probes to an accuracy of 3 %.

The 100-nm $YBa_2Cu_3O_7$ films were grown on a sapphire substrate by using a CeO_2 sublayer. The quality of the films were characterized by x-ray diffraction, DC resistivity, and dynamical impedance. The superconducting onsets were no less than 86 K, the transition width was within 4 K.

In pulsed magnetic field, heating of HTSC films occurs. Unfortunately, the conditions of the experiments do not allow us to measure the temperature dynamics during the pulse. That is why, we have carried out an upper estimation of the heating for pulse of MC-1 generator. We have taken into account temperature transmission into the substrate and contact temperature resistance of a film/substrate boundary. The calculation were performed for two possible regimes of the magnetic flux flow in a superconductor, namely, the flux flow and hard superconductor regimes. At initial temperature of 5 K the upper estimation of temperature of the film at 350 T is 10.5 K. At initial temperatures higher than 15 K the heating becomes unimportant.

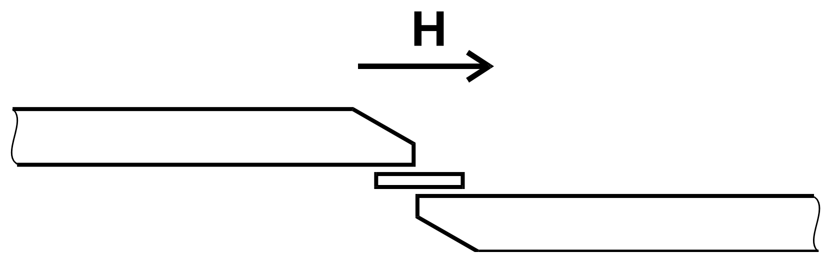

Fig. 1. Position of the film between waveguides.

Measurement of the complex coefficients of transmission and reflection was carried out using a microvawe interferometer. A probing radiation frequency was of 94 GHz. The radiation was led at the magnetic field generators by means of rectangular metal waveguides and directed into the generators by rectangular dielectric waveguides. An interface between two waveguides and a position of the film are shown in Fig.1.

In the dielectric waveguide a hybrid electromagnetic wave of the main mode $HE_{||}$ was initiated. At the end of the waveguide the wave was transformed into nearly a plane electromagnetic wave that was incident on the film at some angle. Transmission of a plane electromagnetic wave through the film and substrate was analysed by a method of impedance recalculation [13]. A solution of the inverse problem enabled to find the complex conductivity of the film from either the transmission or reflection signals. The dependence of the complex conductivity on the magnetic field at initial temperature of 5 K is shown in Fig.2. It can be seen that the independent calculation of the complex conductivity from the transmission and reflection signals are in a qualitative (and, in the case of the real part of the conductivity, even in a quantitative) agreement.

Detailed descriptions of the experimental techniques and the method of the complex conductivity calculation are given in ref. [9,10].

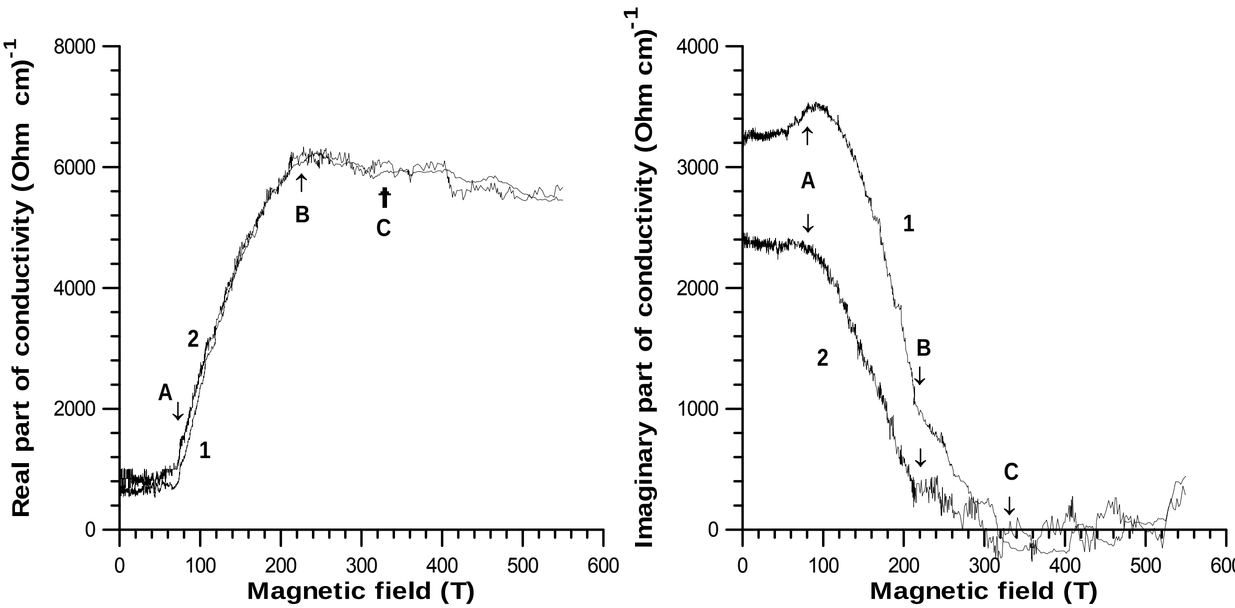

Fig.2. Real and imaginary parts of the conductivity of the YBCO film calculated from the transmission and reflection signals. Initial temperature of the film is 5 K. Curves labelled 1 are from the transmitted signals while those labelled 2 are from the reflected signals.

2. Magnetic phase diagram

Few phase regions can be distinguished in Fig. 2. In weak magnetic field the imaginary part of the complex conductivity predominates. At approximately 75 T (point A) a sharp increasing of the real part of the conductivity, and a decreasing of the imaginary part are observed. Let us mention that ђ□ђ□it is impossible for a single vortex model [14] to explain the increasing of the real part with increasing of magnetic field (in this case $\sigma \propto H^{-1}$). Within a framework of the Portis model [15,16], in which two sorts of vortices are supposed to exist (free and pinned), the behaviour of the complex conductivity can be explained in the following way. In our case, the probing frequency (94 GHz) coincidences with the pinning frequency in order [17]. Then the conductivity of HTSC can be represented as

$$\sigma^{-1} = \left\{ i \frac{C_1}{\left[1 - f(T)\right]H} \right\}^{-1} + \left\{ \frac{C_2}{f(T)H} \right\}^{-1}, \qquad (2)$$

where C_1 and C_2 are real constants, and $C_1 \approx C_2$. One can see from here that at sharp increasing of the fraction of free vortices $f(T)$ the increasing of the real part and the decreasing of the imaginary part occur. By this means the behaviour of the conductivity in the range from point A to point B can be explained [17] if the fraction of free vortices is considered to be a function of both temperature and magnetic field.

Although a small fraction of pinned vortices remains above 210 T (there is a small imaginary part of the conductivity), the sample is mainly in the flux flow regime. The disappearence of the imaginary part of the conductivity and approaching a plateau by the real part (point C) correspond to the estimation $H_{C2}^{\perp}$(8±3 K)=340±40 T. A similar transition was observed at initial temperature of 30 K.

At initial temperature of T_C - 5 K the imaginary part of the conductivity was small. This means that the motion of vortices under the probing radiation is mainly of the flux flow type. At about 15 T the imaginary part disappeared completely that was observed in microwave region near T_C by other authors [18]. This transition is usually associated with flux lattice melting [18]. In the case of the flux flow regime, the approaching a plateau by the real part of conductivity should be interpreted as achievement of the $H_{C2}^{\perp}$ at 45±10 T. This value is in an agreement with the results of $H_{C2}^{\perp}$ measurements in the static [1] and ultrahigh pulsed magnetic fields [6-8].

At low temperatures and weak magnetic fields HTSC is in a vortex glass regime. The increasing of the fraction of free vortices in low temperature experiments is due to the transition from the regime of high density of pinning centers (vortex glass) to the regime of low density of pinning centers (vortex lattice) as magnetic field (and density of vortices) increases. In the last case, some fraction of vortices turned out to be out of pinning centers. In other words, in high magnetic field the density of vortices may significantly exceed the density of pinning centers. For example, at B~200 T a mean distance between vortices is $\sim\sqrt{\frac{\phi_0}{B}} \approx 30$ **Å** only. By this means, the smooth vortex glass - vortex lattice transition takes place in the A-B interval (Fig.2).

From the other hand, it is well known that the transition to the regime of low density pinning centers leads to weakening of effectiveness of the pinning at DC [19] and, hence, to lowering of the critical current. By this means, the irrevisibility line of YBCO [3] may be interpret as a consequent of that glass-lattice transition.

3. Anisotropy of the upper critical magnetic field and the coherence length

While comparing the results obtained above with the former measurements of the upper critical field for the orientation ***c***||**H** [6-8], decreasing of the anisotropy of the H_{C2} attracts an attention. Thus, near T_C the ratio

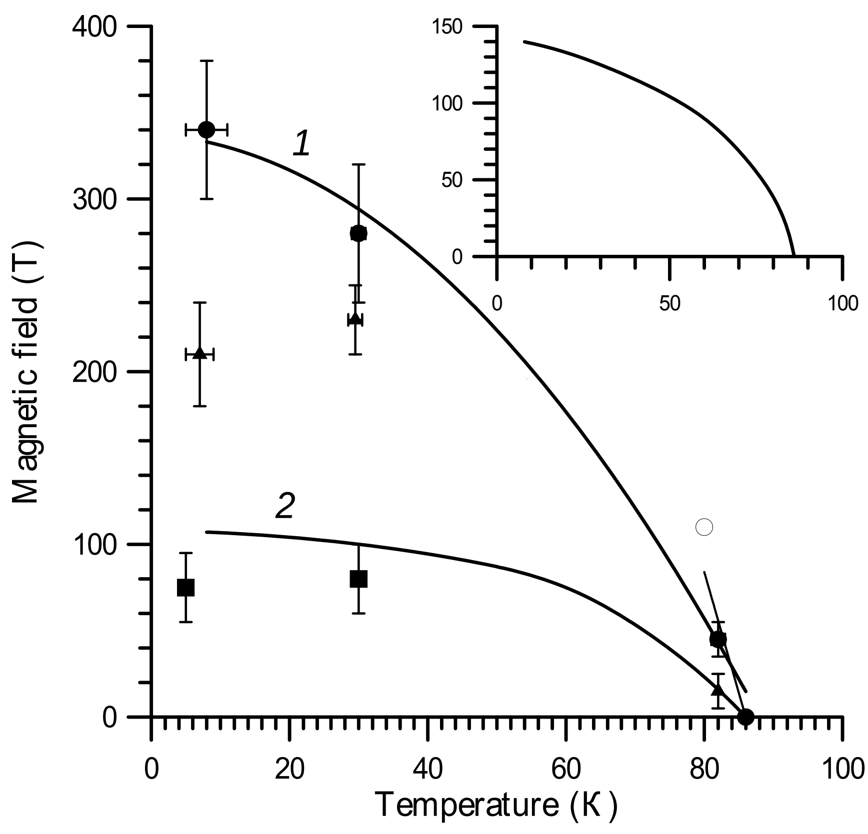

Fig.3. Magnetic phase diagram of $YBa_2Cu_3O_7$ for the orientation of the crysallographic ***c*** axis along the magnetic field. The dark circles is the $H_{C2}^{\perp}$ from this work, light circle is the $H_{C2}^{\perp}$ obtained by resistive method [6-8], the straight solid line is an initial slope of $H_{C2}^{\perp}(T)$ near T_C according to static measurement on singlecrystals [1], the solid line 1 is $H_{C2}^{\perp}(T)$ (a guide to eye), the squares denote point A (Fig.2), the triangles denote point B, the solid line 2 is the reversibility line [3]. In the insert, the $H_{C2}^{\parallel}(T)$ [7] obtained from resistive measurements is plotted.

$\dfrac{H^{\perp}_{C2}(T)}{H^{\parallel}_{C2}(T)}$ account for 5.53 according to the onset of diamagnetism [1]. On the other hand, the ratio $\dfrac{H^{\perp}_{C2}(0)}{H^{\parallel}_{C2}(0)}$ obtain from comparison between data of this work and [7] proved to be 2.43. Such a strong discrepancy can not be explained by an experimental error only.

It is well known that at about 80 K a transition from 3D regime to quasi 2D [20] occurs. Near T_C due to the fact that the distance d between quasi two-dimensional CuO_2 planes is less than the coherence length ***c*** ($\xi^{\parallel}$), HTSC is in the 3D regime. Then, a model of effective mass leads to

$$\frac{H^{\perp}_{C2}(T)}{H^{\parallel}_{C2}(T)} = \frac{\xi^{\perp}}{\xi^{\parallel}} \qquad (3)$$

and the anisotropy of H_{C2} occurs to be large and independent on temperature. As the crossover to quasi 2D regime is passed, the ratio of the critical fields for the different orientations is determined by the following expression

$$\frac{H^{\perp}_{C2}(T)}{H^{\parallel}_{C2}(T)} = \frac{2\sqrt{3}\xi^{\perp}(0)}{d\left(1-\dfrac{T}{T_C}\right)^{1/2}}, \qquad (4)$$

where as usual we suppose that $\xi \propto \left(1-\dfrac{T}{T_C}\right)^{-1/2}$. As can be seen, in quasi 2D regime the $\xi^{\parallel}$ which is a function of temperature turned out to be substituted by d which is independent on temperature. That is why, the anisotropy became a function of temperature. From (4) it is clear that for the quasi 2D regime the anisotropy of H_{C2} decreases as temperature decreases. At 0 K we have $\dfrac{H^{\perp}_{C2}(0)}{H^{\parallel}_{C2}(0)} = \dfrac{2\sqrt{3}\xi^{\perp}(0)}{d}$, i.e. the value of the anisotropy of the upper critical magnetic fields leads to the estimation of the coherence length in the CuO_2 planes $\xi^{\perp}(0)\approx 8{,}5$ **Å** (d=11,7 **Å**).

In conclusion, let us mention that up to now there is no generalization of the MWHH theory to strongly anisotropic superconductors and to quasi 2D superconductors. Nevertheless the magnetic phase diagram obtained is in a qualitative agreement with isotropic MWHH, 3D and quasi 2D models.

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References

1. U.Welp, W.K.Kwok, G.W.Crabtree et al., Magnetic Measurement of the Upper Critical Field of $YBa_2Cu_3O_7$ Single Cristal. Phys. Rev. Lett. 1989. V.62. No.16. P.1908-1911
2. K.Maki, Physics 1. 1964. p.17; N.R.Werthamer, T.Helfand, and P.C.Hohenberg, Temperature and Purety Dependence of the Superconducting Critical Field, H_{C2} III. Electron Spin and Spin-Orbit Effects. Phys. Rev. 1966. V.147. p.295
3. K.Nakao, N.Miura, K.Tatsuhara et al., Magnetic Hysteresis of $YBa_2Cu_3O_{7-x}$ Single Crystals in Very High Magnetic Field above 100 T. Phys. Rev. Lett. 1989. V.63. No.1. P.97-100
4. A.I.Pavlovskii, N.P.Kolokolchicov, V.V.Platonov et al. Physica C 1989. 162-164. p.1659
5. A.I.Golovashkin, O.M.Ivanenko, Yu.B.Kudasov et al., Low temperature measurement of H_{C2} in HTSC using megagauss magnetic fields// Physica C. 1991. V.185-189. P.1859-1860

6. J.D.Goettee, J.S.Brooks, W.J.Skocpol et al., Megagauss Exploration of H_{C2} and Vortex Dynamics in $YBa_2Cu_3O_{7-x}$ Thin Films. Physica B. 1994. V.194-196. P.1805-1806
7. J.L.Smith, J.S.Brooks, C.M.Fowler, et el., Low-Temperature Critical Field of YBCO// Jour. Supercond. 1994. V.7. No.2. P.269-270
8. J.L.Smith, C.M.Fowler, B.L.Freeman et al., Fermi surface and critical field of YBCO. Physica B. 1993. V.186-188. P.104-106
9. A.I.Bykov, M.I.Dolotenko, C.M.Fowler et al., Complex microwave conductivity of $YBa_2Cu_3O_7$ in magnetic field up to 500 T. Physica B. 1995. Vol.211. P.248-250
10. A.I.Bykov, M.I.Dolotenko, C.M.Fowler et al., Complex microwave conductivity of $YBa_2Cu_3O_7$ in magnetic field up to 500 T // Superconductivity: Physics, Science Technology. 1995. Vol.8.- No.1.-P.37-46.
11. C.M.Fowler, R.S.Caird, D.J.Erickson et al,”Explosive Generation of High Magnetic Fields in Large Volumes and Solid State Applications”, in:”Physics in High Magnetic Fields”//Proceedings of the Oji International Seminar,Springer-Verlag, Berlin, (1981) p.54
12. A.I.Pavlovskii, R.Z.Ludaev,“Magnetic cumulation”// in: “Voprosi Sovremennoi Eksperimentalnoi I Teoreticheskoi Fiziki” ed. A.P.Aleksandrov, Nauka, Leningrad:, 1984, P.206
13. L.M.Brehovskikh,”Waves in layered substances”// Edition of AN SSSR, Moscow, 1957
14. J.I.Gittleman, B.Rosenblum, Radio-Frequency Resistance in the Mixed State for Subcritical Currents// Phys. Rev. Lett. 1966. V.16. P.734-736
15. A.M.Portis, K.W.Blasley, K.A.Muller, andJ.G.Bednorz, Europhys. Lett. 1988. 5. P.467
16. E.B.Sonin, A.K. Tagantsev, Zh. Eksp.Teor. Fizik. (JETP)1989. V.95. P.994
17. R.Marcon, R.Fastampa, M.Guira, and E.Silva, Vortex-motion in high-T_C superconductors at microwave frequency. Phys. Rev. B. 1991. V.43. No.4. P.2940-2945
18. N.-C.Yen, U.Kriplani, W.Jiang et al., Microwave vortex dissipation of superconducting Nd-Ce-Cu-O epitaxial films in high magnetic fields. Phys. Rev. B. 1992. V.48. No.13. P.9861-9864
19. A.M.Campbell, J.E.Evetts, Critical Currents in Superconductors. Taylor and Francis ltd., London. 1972.
20. H.Safar et al., Experimental evidence for a multicritical point in the magnetic phase diagramm for mixed state of clear , untwinned $YBa_2Cu_3O_7$. Phys. Rev. Lett. 1993. V.70. No.24. P.3800-3803