RESPONSE PECULIARITIES OF GRANULAR FILMS CARRYING DIRECT OR ALTERNATING TRANSPORT CURRENT

V. F. Drobot'ko, A. M. Grishin, V. A. Khokhlov

Donetsk Physico–Technical Institute, Ukrainian Academy of Sciences, 72, R. Luxemburg Str., 340114 Donetsk, Ukraine

The effect of both direct and alternating current on the diamagnetic susceptibility of the granular YBCO films was experimentally studied. The direct transport current is found to shift the diamagnetic response onset to a lower temperature region. The fine structure appears on the $\chi''(T)$ curve at the small exiciting fields H_{ac} with the increase in the transport current. There are $\Delta\chi'$ jumps on the $\chi'(T)$ dependency corresponding to the fine structure maxima $\chi''(T)$. It is shown that such a method to study HTSC films makes it possible to identify any kind of current loops at the sample temperature lower than that of superconducting transition as well as to evaluate the $j_c(T)$ dependency for each kind of the loop. Nonlinear induction of magnetic field was observed in the $R(T)$ drop temperature interval when transport current at 10 kHz frequency and amplitude from 0.25 to 7 mA (maximal d j_{tr} = 88 A/cm^2) was driven through the film. The observed nonlinear signal is shown to be the superposition of the following two effects: nonuniform distribution of superconducting transition temperatures T_{ci} over the film surface and the e.m.f. due to the electric field E corresponded to the transport current. $U''(T)$ signal and drastic drop of $U'(T)$ are observed at the temperature coinciding with one for diamagnetic response onset and $T_{R=0}$. This temperature is shown to shift towards the lower temperature region as amplitude is increasing in accordance with the linear law. Nonlinearity reaches its maximum value just at the temperature of the resistive transition $T_{R=0}$. Here the higher even harmonics appear together with the odd ones.

Introduction. Thin HTSC-films are known to be inhomogeneous. Typical dimensions α of single-crystalline blocks in epitaxial [1] and of granules in polycrystalline [2] films vary from 100 A to several mms. Because of the coherence length ξ smallness in these films there are independent superconducting regions (crystallites) weakly interconnected by, generally speaking, spatially inhomogeneous Josephson junctions. Spatial inhomogeneity of the Josephson junctions is, to a known extent, due to the growth conditions of a given sample. And the critical-current value for the Josephson junctions in HTSC-ceramics can be, for example, conditioned by inhomogeneous oxygen concentration in the junctions [3].

In HTSC-materials the value of critical current and its temperature dependence can be determined by the widely used contactless method of measurement of the quadrature part of the diamagnetic susceptibility [4–7]. The $\chi''(T)$ dependence shows a maximum which is due to hysteresis losses for the reversal of sample magnetization. Within the critical-state model the maximum losses correspond to such $j_c(T)$ value when the existing field H_{ac} forces the magnetic flux to penetrate to the very centre of the sample. For example, for a flat sample of thickness d, when H_{ac} plane of plate [8]

$$j_c = \frac{cH_{ac}}{2\pi d}.$$

When studying the diamagnetic susceptibility in the granular thin films YBCO in superlow magnetic fields we have found the field of ~ 5 mOe below which the hysteresis losses have lowered suddenly ($\chi'' = 0.02\chi'_{max}$) and single maximum at $\chi''(T)$ dependence splits into six separate peaks [9]. The field depedences of the temperatures of maxima of those peaks (according to expression (1)) pointed to the existence of critical currents flowing in the film and differing in their value. Different values of the critical temperatures have been determined by extrapolating the dependences to $H_{ac} = 0$. These data permit us to suppose that the alternating field H_{ac} induces loop currents in the film whose value is determined by the properties of Josephson junctions. In the region of defects the film structure may vary, e.g. its oxygen index which determines the local values of critical current and critical temperature. As a result, various intergranular currents appear flowing by closed loops of different shapes including the circular one. This circumstance confirms observation of the dissipative losses fine structure in YBCO single crystals [10,11]. In the single crystals the twinning boundaries play the role of weak links. In the better single crystals there is only one narrow peak on the temperature dependence of $\chi''(T)$ [11,12]. The diamagnetic response of the film occurs when the current loops consisting of a large number of granules are formed there. Initiation of the loops coincides with the temperature $T_{R=0}$ of sample when its resistance becomes zero [12,13].

Different $j_c(T)$ dependence typical of different current loops allows us to suppose that the measurements, in weak exciting field, of the susceptibility $\chi(T)$ of the film with the transport current flowing on it, will make better separation of the diamagnetic response from each current loop on the temperature scale. If the sum of transport current and shield current of the loop is in excess of the critical current for the latter one then the loop disconnects and there should be no diamagnetic response. There will be no signal up to the moment when the temperature of the sample decreases so that the critical current of the loop does exceed the sum of transport and shielding ones. The higher is transport current the more is the displacement of the response from both the separate current loops and the whole sample on the temperature scale.

The alternating transport current should also displace the onset of the diamagnetic response initiation on the temperature scale. The important peculiarity of this response is the presence of a second-harmonic signal in the spectrum, since in this case the disconnection of current loops of the sample will occur twice for the period of alternating current oscilations. Besides, the alternating current-induced Lorentz force effecting the vortices in a superconductor may lead to some peculiarities in the temperature behaviour of the average sample magnetization and, thus, of the signal received.

The experiment and samples. The diamagnetic response of the films carrying direct transport current has been studied using an inductance measurement system including a modified Harshtorn bridge with the original design of its low-temperature part. To increase the inductive coupling between the sample and the receiving coil, the latter has been made flat. The measured film is pressed to its surface. The compensating and phase coils are also flat. The well intercompensated receiving and compensating coils are separated by a sapphire rod and are aligned with the exciting coil and placed inside it. The use of a sapphire rod, to whose ends the receiving and compensating coils are glued has made it possible to obtain high thermal stabilization of the bridge under the temperature measurements of the films. The signal of bridge unbalance was amplified by the double-channel lock-in amplifier to measure both the phase-coincident U' and quadrature U'' signals of HTSC film diamagnet. These signals were recorded by X–Y recorders.

In the case of studying the response from the sample carrying the alternating current the compensating coil was disconnected and the signal went from the receiving coil directly to the input of lock-in amplifier. In both cases the temperature of sample varied from low to high. The sample was screened from the electic field by the lead screen. The studies were performed at the modulation frequency of 10 kHz. Spectrum of the signal from the receiving coil was recordered using the spectrum analyzer.

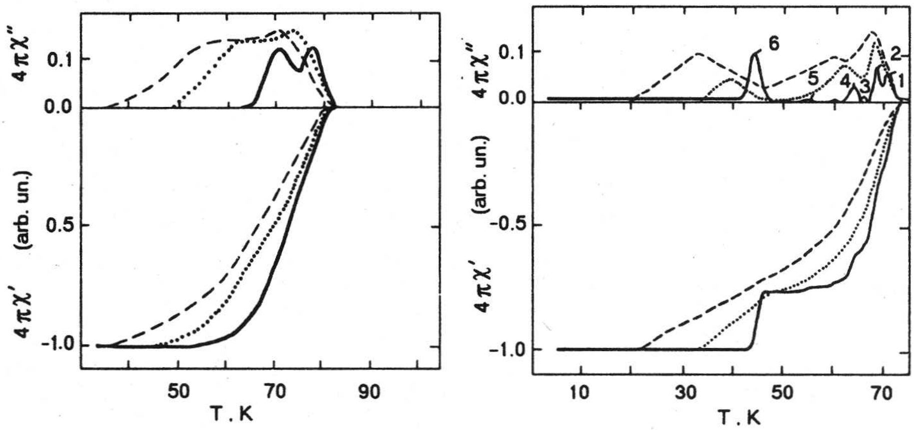
The studies were performed for the YBCO films obtained by the method of the magnetron sputtering. Sapphire was taken as the substrate upon which the ~ 0.1 μm thick sublayer of ZrO_2 was deposited. The films were 0.8 μm thick. The X-ray diffraction analysis shows that the both samples are very well textured and contain 68% and 72% of $YBa_2Cu_3O_{7-x}$ phase (samples № 1 and № 2 respectively).

The response from the film carrying the direct transport current was measured first on the sample № 1 at the range of exciting magnetic fields H_{ac} of 0.1–15 mOe and the transport current of 0–24 mA which corresponded to the average current density j_{tr} = 0–254 A/cm^2. The study of the 10 kHz alternating transport current effect on the response of YBCO film was performed with the amplitude values of the alternating current of 0.25–7 mA (j_{max} = 88 A/cm^2) on the sample № 2 because it was more homogeneous magnetically.

Experimental results. Fig. 1,*a* shows the field dependence of the diamagnetic response of the sample № 1. It is seen that with the increase of existing field H_{ac} the amplitude curves $\chi'(T)$ shift towards the low-temperature region, and curves $\chi''(T)$ extend and their maxima become smooth. The temperatures of these two maxima T_m shift to the region of low temperatures, depending on the H_{ac}, by different laws — the linear decrease of T_m with H_{ac}, increase for the low-temperature maximum and power dependence $1 - T_m/T_c \sim H_{ac}^{2/3}$ for the high-temperature one, as is shown in Fig. 2.

When the transport current I_{tr} = 20 mA (j_{tr} = 210 A/cm^2) passes through the film the picture changes essentially (see Fig. 1,*b*). In the field H_{ac} = 1 mOe at least six peaks appear on the $\chi''(T)$ curve instead of two, the first, second and fifth ones have complex structure. A break on the $\chi'(T)$ curve and a jump of $\Delta\chi'$ of the definite value correspond to each $\chi''(T)$ maximum. With field increase H_{ac} > 3 mOe there remain only three maxima on the $\chi''(T)$ curve which shift towards the low-temperature region with further increase of the field, and two high-temperature maxima start merging. On the $\chi'(T)$ curve a break is well-defined corresponding only to the low-temperature maximum of a $\chi''(T)$ curve. The temperature T_m of two high-temperature maxima on the $\chi''(T)$ dependence changes with the field according to the law of $1 - T_m/T_c \sim H_{ac}^{2/3}$ and the low-temperature maximum linearly shifts with the field (see Fig. 2).

Fig. 1,*c* shows the $\chi'(T)$ and $\chi''(T)$ dependencies at H_{ac} = 1 mOe and different values of the transport current. It is seen that with the increase of the average density of the transport current up to 110 A/cm^2 the $\chi''(T)$ curve becomes more complex. At j_{tr} = 254 A/cm^2 there are six maxima of the dissipative losses, the third, fourth and sixth maxima do not practically overlap. On the $\chi'(T)$ curve the typical breaks are seen due to the appearing of the dissipative response of the corresponding current loops. With the increase of the transport current the temperature of the diamagnetic response onset T_{on} is shifted to the low-temperature region. The similar displacement of the diamagnetic response onset was found at



a *b*

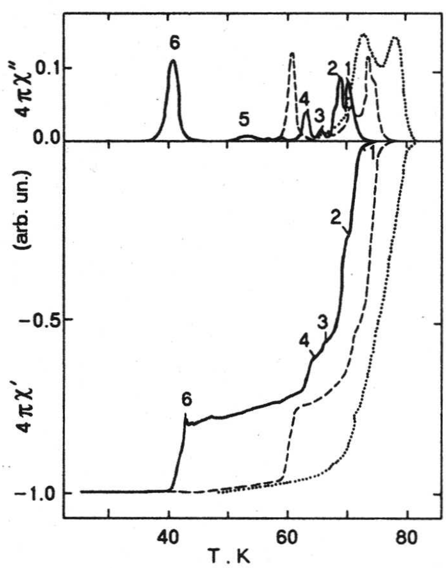


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Fig. 1. Temperature dependence of $\chi'(T)$ and $\chi''(T)$ for YBCO film: a — $j_{tr} = 0$, solid line — $H_{ac} = 1$ mOe, dotted line — $H_{ac} = 8$ mOe, dashed line — $H_{ac} = 15$ mOe; b — $j_{tr} = 210$ A/cm^2, solid line — $H_{ac} = 1$ mOe, dotted line — $H_{ac} = 8$ mOe, dashed line — $H_{ac} = 15$ mOe; c — $H_{ac} = 1$ mOe, dotted line — $dj_{tr} = 0$, dashed line — $j_{tr} = 110$ A/cm^2, solid line — $j_{tr} = 254$ A/cm^2

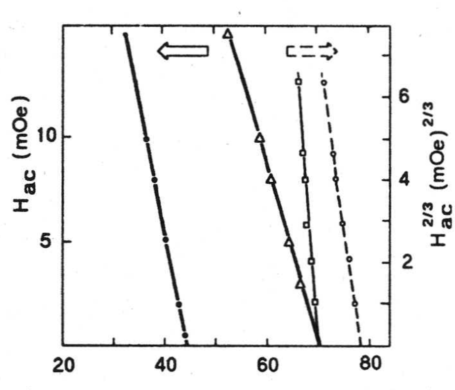


Fig. 2. The shift of T_m's of both high-temperature and low-temperature peak on $\chi''(T)$ – curve for YBCO films as a function of the exciting field strength H_{ac} : ○, △ — $j_{tr} = 0$; ●, □ — $j_{tr} = 210$ A/cm^2

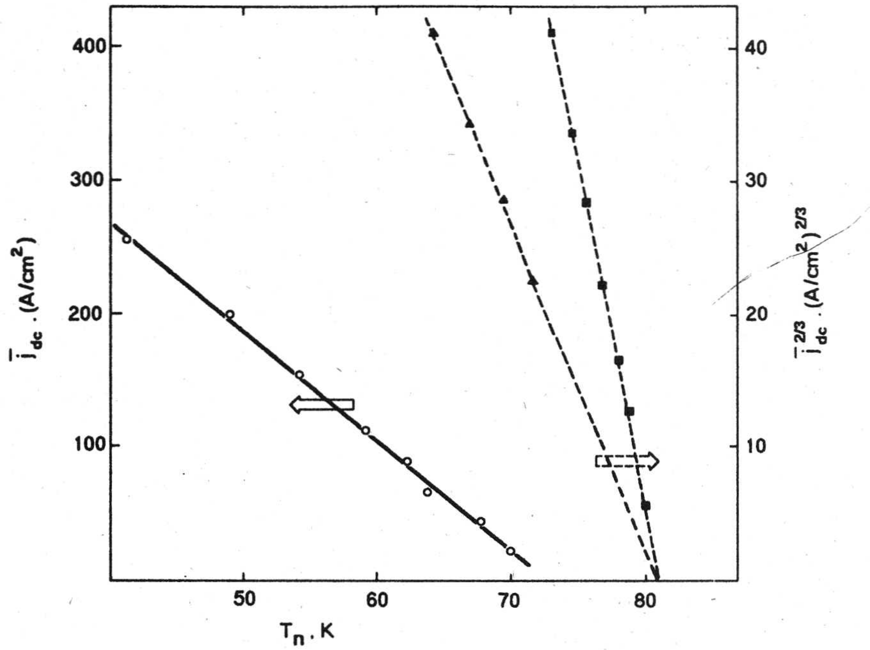


Fig. 3. Dependence of appearance of the first (■), fourth (▲) and sixth (○) signals of $\Delta\chi'$ due to corresponding types of current loops of samples, on the value of average densities of the transport current of j_{tr}

YBCO ceramic samples in [14]. It should be noted, when the $\chi'(T)$ dependence was studied at different exciting magnetic fields, the temperature of diamagnetic response onset did not change. Under the similar investigation, but when the transport current I_{tr} = 20 mA is transmitted through the film, the temperature of diamagnetic response onset has shifted for 7 K to the low-temperature region and did not change with H_{ac} increase.

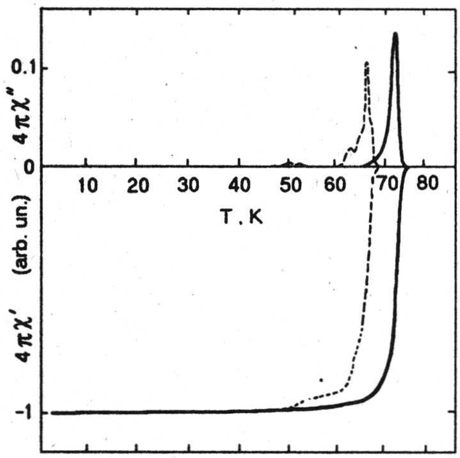


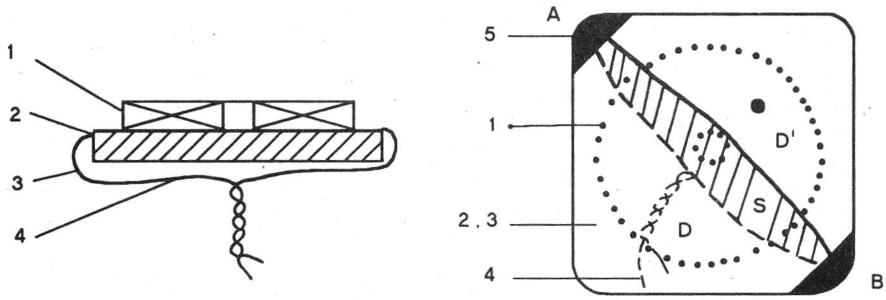
Fig. 4. Temperature dependence of χ' and χ'' of sample № 2 (after degradation): H_{ac} = 5 mOe, solid line — j_{tr} = 0, dashed line — j_{tr} = 110 A/cm^2

With the results of $\chi'(T)$ and $\chi''(T)$ measurements at different values of transport current we have found the dependences for the shift of the temperature of diamagnetic response onset both for the whole sample T_{on}, and the temperatures of diamagnetic response of the circuits corresponding to the fourth T^4_{on} and sixth T^6_{on} maxima dissipative losses. The results are shown in Fig. 3. From the figure it follows that with the increase in j_{tr} the temperatures T_{on} and T^4_{on} decrease according to poweer law proportionally to $j_{tr}^{2/3}$ and the temperature

T_{on}^{6} changes linearly with the transport current.

Fig. 4 illustrates the $\chi'(T)$ and $\chi''(T)$ dependences for sample № 2 (after degradation as a result of multiple He filling) at the field of H_{ac} = 0.5 mOe in the absence of transport current (and with it, j_{tr} = 110 A/cm^2). It is seen from this figure that $\chi''(T)$ signal from the sample with no transport current has one maximum, i.e. it may be considered homogeneous in the magnetic aspect. The transport current has made it possible to slow that, in fact, in the film there exist at least five current loops, three having very close values of T_{ci} and j_{ci} and the two ones (their quantity is very small) — lower values of T_c and j_c, so they occur in the spectrum of the signal only at a lower temperature (near 50 K).

When the response from film № 2 , at which the alternating transport current



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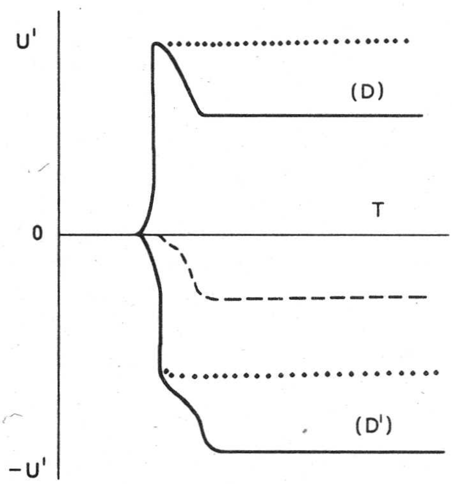

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Fig. 5. The scheme of the experiment: *a* — view from one side; *b* — view from above; *1* — receiving coil, *2* — YBCO film, *3* — substrate, *4* — current connectors, *5* — current contacts. A conventional line of transport current flow through the film is shown by the solid line. Points *D* and *D'* represent schematically positions of current connectors twisting at two configurations of the experiment; *c* — the schematical temperature dependence of fundamental harmonic of co-phase signal at different (*D* and *D'*) configurations of the experiment (see Fig. 1,*b*). The separation of two contributions to the induced signal $U'(T)$ is shown: dotted line is direct magnetic pick-up witk the changed sign depending on changes of the current loop configurations; dashed line is the extra-e.m.f. conditioned by the electric field of the transport current; solid line is the summary of U' signals

flows, was studied, the sample with leads (see Fig. 5,*a*) was placed onto a receiving coil and pressed to it using a plug.

To monitor the properties of the studied film by the ordinary technique the temperature dependences $\chi'(T)$ and $\chi''(T)$ of the sample obtained at different amplitudes of the exciting field H_{ac} have been measured (see Fig. 6). It is seen that

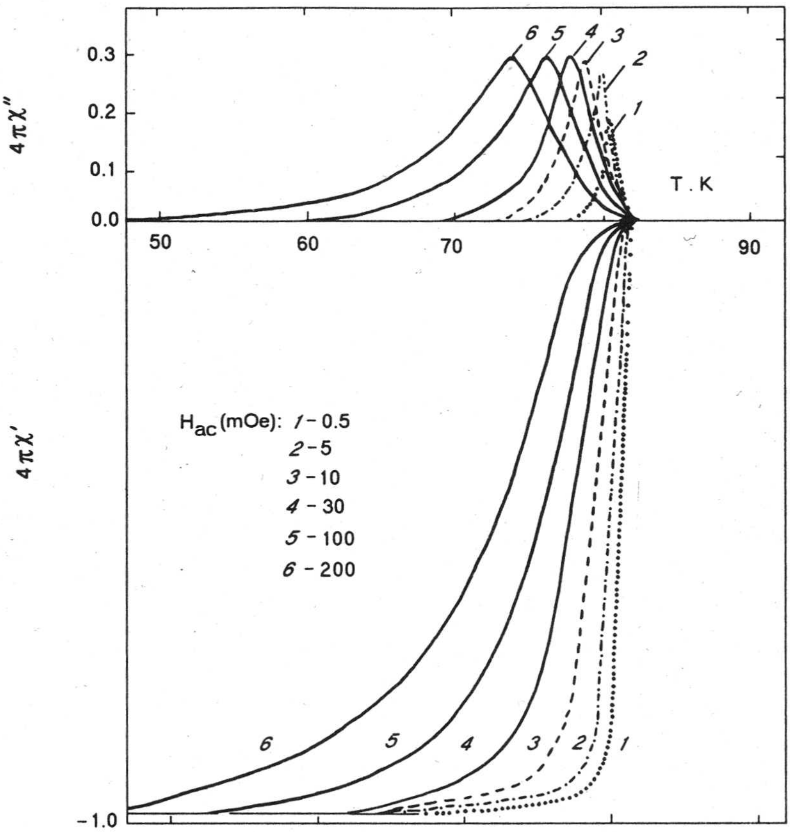

Fig. 6. Temperature dependence for the diamagnetic susceptibility of χ' and χ'' (sample № 2) at different amplitudes of the exciting field H_{ac} at 10 kHz

the curves are of usual form with the onset temperature of diamagnetic response near 82 K . With the increase of H_{ac} amplitude of the external field H_{ac} the temperature of the maximum T_m of $\chi'(T)$ dependence shifts to the low-temperature region by the linear law (see Fig. 8) at $H_{ac} > 1$ mOe, though it had the break at $H_{ac} \sim 12$ mOe.

The results of $U'(T)$ and $U''(T)$ measurements performed at $I_{\sim} = 1$ mA are shown in Fig. 7. It also shows the $R_0/R_0(T_1)$ dependence of the sample obtained with the measuring current of 1 mA. Let us consider the behaviour of $U'(T)$ from the coil which is observed whereas there is no signal of $U''(T)$. This signal is due to the alternate field penetrated the sample and screened only slightly by it because of high resistance of the sample at those temperatures. The source of this field is the current loop formed by untwisted ends of the leads and effective stream-line of the sample (see Fig. 5,*c*). The effective stream-line is a conventional line to the right and left of which the current density is the same. As the rough approximation it may be considered that total current flows at the sample along this line. The loop area is S . The rough estimation for the field created by this loop, at $I_{\sim} = 1$ mA, is of 2 mOe approximately. With the decrease of sample temperature below $T_1 = 88$ K a

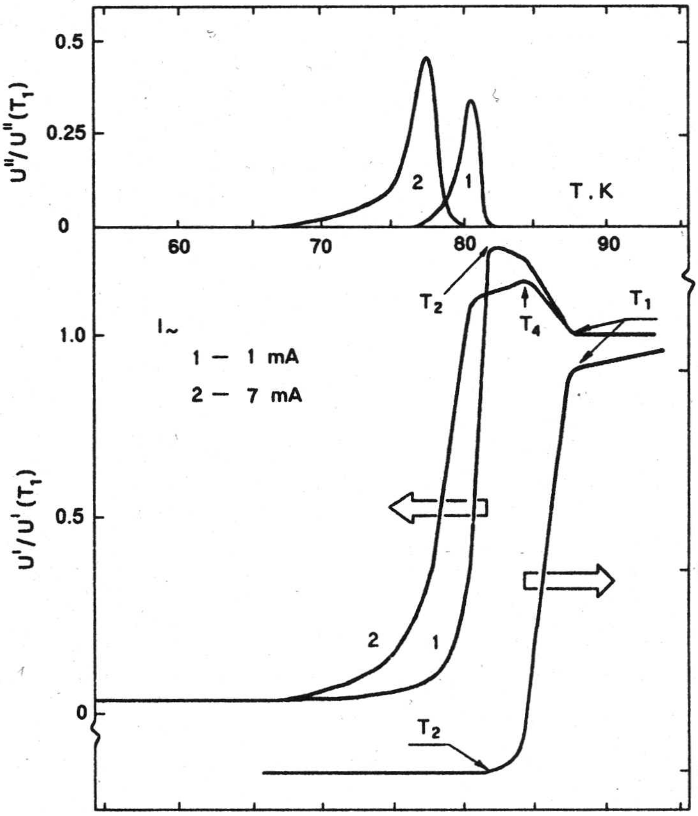

Fig. 7. Temperature dependencies of co-phase U' and quadratic U'' signals in the pick-up coil at 10 kHz and two different transport current amplitudes 1 and 7 mA. Here the temperature dependence of resistivity R at I = 1 mA normalized to $R(T_1)$ is presented

rise of $U'(T)$ signal is observed, then at a temperature T_2 the signal dropped rapidly similar to the behaviour of $\chi'(T)$. The $U''(T)$ signal occurs simultaneously with the sudden drop of $U'(T)$. It is very similar to $\chi''(T)$ signal but its amplitude is larger than that of $\chi''(T)$. At 1 mA the temperature T_2 equals 82.3 K and practically coincides with the temperature of $\chi'(T)$ and $\chi''(T)$ signals appearance. In the temperature range $T_1 - T_2$ the behaviour of $U'(T)$ signal depends on the alternating current amplitude. It should be noted that the temperature T_1 corresponds to that of the onset of sudden decrease of sample resistance, and T_2 (for transport current $I_{\sim}$ = 1 mA) to the temperature at which R becomes zero. Coincidence of the temperature $T_{R=0}$ and temperature of diamagnetic responce occurrence was also noted [13,15].

As it was expected, T_2 shifted to the low-temperature region with the increase of alternating current amplitude. Fig. 8 shows the dependence of T_2 shift on value of the current $I_{\sim}$. Also it shows the dependence of the temperature of $U''(T)$ maximum as a function of $I_{\sim}$. It is seen that all the dependences presented in Fig. 8 are of linear character and this is clear, since they (with their coefficients) show the

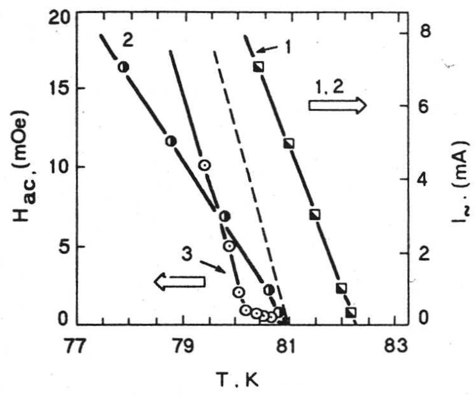

Fig. 8. T_2 dependence on a. c. amplitude $I_{\sim}$ (*1*); maximum $U''(T)$ temperature dependence on amplitude $I_{\sim}$ (*2*) ; maximum $\chi''(T)$ on H_{ac} (*3*); dashed line curve *3* is $j_c(T)$ dependence obtained by separation of two effects: hysteresis losses and the onset shift of the screening current

temperature dependence of the critical current. The temperature dependence of U'' maximum on $I_{\sim}$ is due to two mechanisms: shift of T_m together with T_2 at the expense of current loop breaking, and shift of loop S dependent on the amplitude of variable magnetic field together with the alternating current amplitude. While excluding the influence of T_m shift at the expense of T_2 shift we obtain the dependence of T_m on the magnetic field of loop S (the dot line in Fig. 8). By matching the scale of the temperature dependence of χ'' maximum on H_{ac} these lines can be made parallel which permits us to compare the fields of loop S and the known field of excitation from the external coil, measuring the $\chi''(T)$. It follows from the comparison that 1 mA of the alternating current corresponds to the field of the same order as the field found from the evaluated area of loop S . Note that temperatures, to which those dependences are extrapolated, are close whereas the temperature to which the $T_2\,(I_{\sim})$ dependence is extrapolated is considerably higher.

Fig. 9 shows the temperature dependences of $U'(T)/U'(T_1)$ signal and $R_0/R_0(T)$ taken at different constant magnetic fields H_{dc} . The measurements were made after the change of lead twisting point from D to D' (see Fig. 5,*a*). Note the following peculiarities of the curves:

a) with H_{dc} increase the temperature T_2 shifts to the low-temperature region as is under the increase of the alternating transport current (see Fig. 7). The temperature of the zero sample resistance shifts to this region as well. Unfortunately, our device for the $R(T)$ measurement is not enough sensitive to reveal the exact coincidence of temperatures $T_2\,(H_{dc})$ and $T_{R=0}\,(H_{dc})$;

b) on the $U'(T)/U'(T_1)$ dependences (Fig. 9) there exists a temperature T_3 above which all the $U'(T_3,H_{dc})$ curves overlap. At this temperature the resistance of the sample approximately amounts 30% of its value at T_1 ;

c) on the $U'(T)/U'(T_1)$ dependences, at different H_{dc} and $U'(T,I_{\sim})/U'(T_1)$, (see Figs. 7 and 9) there exists a temperature T_4 at which the slope of $U'(T)/U'(T_1)$ dependences changes. At his temperature the resistance of the sample approximately amounts 6% of its value at T_1 .

Fig. 10 shows spectra of signal from the receiving coil near T_2 obtained when the alternating current of 3 mA amplitude is transmitted through the sample. It is seen that apart from the odd harmonics which should be present in the spectrum of $\chi(T)$ signal [7] there are not only the second harmonic, as was expected, but even

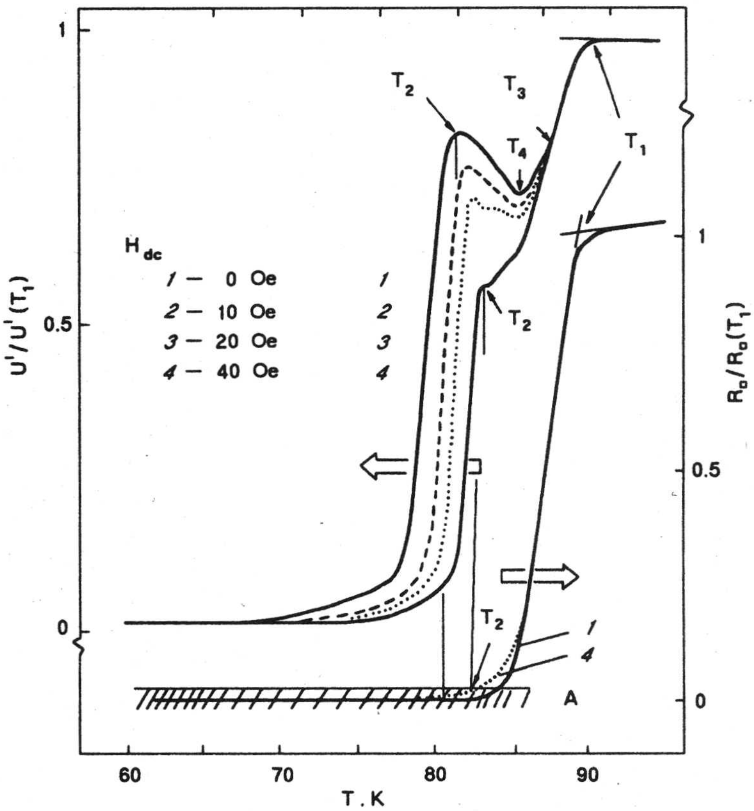

Fig. 9. Dependence $U'(T)$ normalized to the value of U', T_1 and different values of H_{dc}. Dependence $R(T)$ normalized to $R(T_1)$ by A a region of deviated insensitivity is marked. Discussion for $T_1 - T_4$ see in the text

harmonics of the highest order as well. The maximum of harmonics amplitude is seen near T_2 .

Discussion. Let us examine some possible reasons why the $\chi''(T)$ signal acquires a "multi-peak" nature during the passage of a constant transport current through the film. By virtue of the Meissner effect, this current is displaced to the edges of the sample. In other words, a current gradient exists over the cross section of the film.

1. Let us assume that two types of current loops (identical within each type) exist in a film. They are distributed in a statistically uniform way over the area of the sample. The values of T_c and $j_c(T)$ are identical for the loops of a given type. The diamagnetic response disappears because of a rupture of the current loops at $j_{tr} = j_c$. If there is a gradient in the transport current, then certain loops would naturally be broken at a relatively high temperature, and others at a relatively low temperature. These effects could give rise to the multi-peak nature of the $\chi''(T)$ signal. We do not know the distribution of the transport current over the cross section of a granular film. However, if we take this film to be a continuous Josephson medium then we can use the model of a solid superconducting bar, in a first

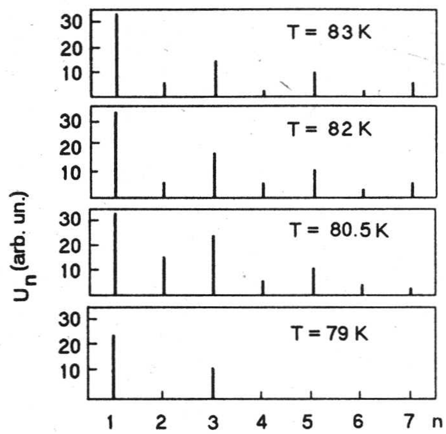

Fig. 10. The spectral characteristics of signals produced by the receiving coil at four different temperatures, measured at I_{tr} = 3 mA

approximation [16]. It was shown in Ref. 16 that the gradient of the transport current is significant at a distance greater than 0.9 of the width of the bar, i.e., at the very edge of the film. When we further note that the ratio of the areas of the pickup coil and of the sample are roughly the same, we see that we can assume that the gradient of the transport current in the film would be essentially incapable of leading to multiple peaks in the dissipative response $\chi''(T)$.

2. We now imagine that there are (again) current loops of two types in the film, but now there exists a set of loops, with approximately equal T_c's but different $j_{ci}(T)$ curves, within each type. In the absence of a transport current, the superposition of the diamagnetic responses from the loops of a given type results in a single signal. When a transport current is passed through the film, however, the current loops with the lower critical current begin to rupture first. If the diamagnetic response from these loops is to reappear, the sample temperature must be lowered to the point that j_c is above j_{tr} . As a result, the signal from these loops shifts to a lower temperature. As j_{tr} increases, and as the difference between the slopes of the $j_{ci}(T)$ curves for the different current loops increases, the separation of the corresponding dissipative-loss signals on the temperature scale becomes greater. This model thus appears to be the most plausible one for explaining the observed results.

Now, come to the discussion of results obtained when studying the response from the film carrying the alternating transport current. As is has already been mentioned, the $U'(T)$ signal is due to the magnetic field of the loop formed by the untwisted ends of leads and the effective stream-line. This field is slightly screened by the eddy currents of the sample at $T > T_1$ (the depth of the skin effect of the film at 10 kHz at the above temperatures is of the order of 1.5 cm). So, a linear approximately the same (by virtue of $\sigma(T)$ change) signal of U' is induced in the receiving coil at $T > T_1$. When the sample goes over to the superconducting state, the magnetic field of the loop is screened by the diamagnetic currents of the film and signal at the receiving coil disappears. The efficiency of loop field screening is defined by the magnetic susceptibility of the sample, so the e.m.f. induced in the receiving coil bears an information about the non-linear $\chi(T)$ of the film.

In the temperature range $T_1 - T_2$ at the receiving coil an additional e.m.f. occurs whose sign does not change with the change of the sign of field from loop S . To check the statement the following experiment has been performed. The point where the leads are twisted was transfered over to the opposite side of the line connecting points A and B , i.e. from point D to D' (see Fig 5,*c*). Signal from the receiving coil has changed its sign (see Fig 5,*c*). In the region $T_2 < T < T_1$ the additional e.m.f. has conserved its sing resulting in the change of the shape of $U'(T)$ signal from lock-in amplifier (see Fig. 5,*c* and real curves, Figs. 7 and 9).

It should be noted that when studying the diamagnetic response from the sample carrying the direct transport current, we did not observe the occurrence of signals in the temperature range $T_2 < T < T_1$.

An assumption of the spatial inhomogeneity of the sample may be one of the possible reasons for the occurrence of an additional signal at the receiving coil in the temperature range $T_2 < T < T_1$. Indeed, because of the inhomogeneous distribution of magnetron HF plasma on substrate surface the temperature of transition to the superconducting state for the film formed at substrate edges is as usual higher than in its centre. The *X*-ray studies have confirmed the sample to be spatially inhomogeneous. If the sample is spatially inhomogeneous then when in the granular film the temperature decreases from T_1 , because of the inhomogeneous distribution of granules with respect to T_c [7], more and more superconducting granules, being a short-circuit for the stream-lines, are formed in the sample. At further temperature decrease the granules first form the superconducting chains and then the elements of the percolation network. If granules of equal T_{ci} are nonunformly distributed over sample area then the effective stream-line will shift to the region of higher concentration of granules of equal T_{ci} , thus increasing or decreasing the area of loop S depending on position of point D (see Fig. 5,*b*). It may be supposed that at T_3 (see Fig. 9) separate cells of the percolation network occur. The cells of this network can trap flux bundles around which the superconducting current circulates. If the transport current flowing through such a cell is higher than its critical currents, then current loop is broken and the magnetic flux of this loop is shifted to another loop or non-superconducting space under the influence of the Lorentz force. Such motion of the flux is equivalent to initiation of the additional resistivity of the sample. In this situation the middle stream-line will shift aside, where such processes are less frequent. So, the observed pattern of $U'(T)$ behaviour in the region of temperatures $T_2 < T < T_1$ can be explained by spatial inhomogeneity in distribution of superconducting granules in the sample. The higher is the transport current and so is the amplitude of a. c. magnetic field penetration into the specimen, the more is the probability of destruction if superconductivity for granules at $t \Rightarrow T_1$ and superconducting loops surrounding the magnetic-flux beams at $T < T_4$. So, the signal from the receiving coil will decrease with an increase of the transport current (which is the case in the temperature range $T_4 - T_2$, Fig. 7). The temperature T_4 probably corresponds to that of suddent increase of percolation network elements which trap the magnetic flux. If this is so, it becomes clear why it is in the temperature region $T_4 - T_2$ where splitting of the $U(T, H_{dc})$ lines is most pronounced (see Fig. 9).

One more probable reason for the occurrence of an additional $U'(T)$ signal, in the temperature range $T_1 - T_2$, is disappearance of the electrical field E (in a superconductor $E = 0$) existing in it at $T > T_1$. To check this supposition, the following experiments have been performed. Within the same geometry (see Fig. 5,*b*) a copper foil was taken instead of YBCO films and $U'(T)$ signal amplitude was registered. Next, a box was made of the copper foil, the area of the box being equal to that of the sample. A thin cut was made on the other side of the box, to whose edges the twisted current-carrying conductors have been soldered. Such a design practically excluded initiation of the current loop. The field E was conserved equal to that in the case of copper plate. In this case the signal pick-up at the coil was approximately equal to $U'/3$. This signal is schematically shown in Fig.5,c by a dotted line.

In real situation, the $U'(T)$ signal in the temperature range $T_1 - T_2$ is probably due to the both reasons. Since the temperature region $T_1 - T_2$ coincides with the region of sudden change of $R(T)$, then the ability of the installation to register the field E allows us to hope that this temperature region can be found not only in spatially inhomogeneous granular films, but in quasi-epitaxial spatially homogeneous samples.

In the absence of the magnetic field the theory of [7] forecasts the existence of the odd harmonics of susceptibility $\chi(T)$ only this is the direct consequence of central symmetry of the magnetization curve $M(H)$ ($M \Rightarrow -M$; $H \Rightarrow -H$) which, in its turn, is due to the symmetry with respect to time inversion $t \Rightarrow -t$. This conclusion has been confirmed in papers [17, 18]. In constant magnetic field, in the spectrum of diamagnetic response the even harmonics occur [19] because of $t \Rightarrow -t$ symmetry violation. The even harmonics, which appear in the response from the film carrying the alternating transport current, are also, perhaps, due to violation of $t \Rightarrow -t$ symmetry. The second harmonic signal has been observed in [20] under study of YBCO ceramic sample carrying the alternating transport current. Chen and co-workers [21] have observed the second harmonic signal in the region of YBCO resistive transition for the case of ceramic and film YBCO sample. Its maximum coincided with the temperature $T_{R=0}$. Experimentally they solved the problem which was opposite to our one. The alternating signal was measured at potential contacts of a superconducting film with the direct transport current flowing. At the same time, the sample was influenced by the alternating magnetic field, normal to the plane of the film, with $0.1 - 1$ Oe amplitude. They explained the presence of the second harmonic by destruction of superconductivity by the magnetic field of variable sign. In papers [20, 21] only the second harmonic has been observed. In our experiment, occurrence of the even harmonics of highest order in the spectrum of the output signal is probably due to violation of the $t \Rightarrow -t$ symmetry when the alternating current flows over the sample.

Thus, studies of the response of films carrying direct and alternating transport current have shown that:

1. Study of diamagnetic response of granular YBCO films in low exciting magnetic fields permits us to reveal better the magnetic inhomogeneity of such object and estimate the contribution of different current loops, existing in the film, to total diamagnetic response of the sample.

2. Since the temperature of occurrence of diamagnetic response in the films T_2 coincides with the temperature of zero sample resistance, then when measuring T_2 as a function of transport current value we essentially measure the temperature dependence of the critical current.

3. By using the proposed technique for studying the response of a HTSC film carrying the alternating transport current in the region of temperatures corresponding to a sudden change in $R(T)$ ($T_1 - T_2$) we can study the magnetic properties of HTSC films in this temperature region independently as well as determine T_2 from studies of diamagnetic response.

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