Absence of the Transition into Abrikosov Vortex State of Two-Dimensional Type-II Superconductor with Weak Pinning

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The resistive properties of thin amorphous NbO_x films above and below H_{c2} were investigated experimentally. It was shown that near H_{c2} the excess conductivity dependences agree with the predictions of the paraconductivity theory. The current-voltage characteristics in a perpendicular magnetic field remain Ohmic up to a very low magnetic field. This is interpreted as the absence of the transition into the Abrikosov vortex state of a two-dimensional type-II superconductor with weak pinning.

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Before the discovery of high-T_c superconductors (HTSC's) the point of view prevailed that between the first, H_{c1}, and the second, H_{c2}, critical fields type-II superconductors can be only in the vortex-lattice state, first described by Abrikosov [1]. The unusual properties of HTSC's in a magnetic field have stimulated considerable interest in fluctuation effects in type-II superconductors. In addition to the vortex lattice the existence of other states (vortex glass, vortex fluid) is assumed in many works [2,3]. In the majority of papers the influence of fluctuation on mixed state properties of HTSC's was investigated. But a HTSC is an inconvenient object for initial investigation of this phenomenon. The HTSC's have some peculiarities that are not quite understood. Besides, all known HTSC samples have strong vortex pinning. In most of the works the fluctuation influence on properties connected with pinning is investigated. But until now the pinning effect has not been described quantitatively for a real case. A limited number of theories of weak pinning [4] can be compared with experimental data only qualitatively. For this reason numerous experimental confirmations of fluctuation theories of the HTSC mixed state do not look reliable. The experimental data have alternative explanations in almost all cases.

Therefore we think that investigation of fluctuation effects in conventional, low-T_c type-II superconductors (LTSC's) with weak pinning is very timely. The investigation of these objects can help to verify the fluctuation theories of the mixed state. The point of view is widespread so that in LTSC the fluctuation effects are small [2]. But this opinion is not correct for the high magnetic field region. Calculation [5] and investigation [6] have shown that fluctuation effects in the mixed state of conventional "dirty" type-II superconductors are great, no smaller than in HTSC.

The thermodynamic average order parameter is distributed inhomogeneously in a superconductor which is in the Abrikosov state. Therefore properties of type-II superconductors in the mixed state may be separated into two types. It is obvious that the magnetization and the specific heat are connected with the spatial average of the order parameter, whereas the vortex pinning is connected with the inhomogeneous distribution of the order parameter in space. It was shown in [7,8] that the fluctuation essentially alters the spatial average value of the order parameter inside the critical region only. The experimental dependences of the specific heat [9] and the magnetization [10] in the H_{c2} critical region are described by the fluctuation theory of 1D superconductors. The dependences for bulk superconductors are described by the theory of one-dimensional superconductors. The resistive transition in a parallel magnetic field of bulk superconductors is also described by the theory of one-dimensional superconductors [5].

Therefore the fluctuation influence on the order parameter distribution is the most interesting problem now. There are two different theoretical approaches to this problem. In most work (see, for example, [2]) the fluctuations are considered as oscillations of the Abrikosov vortex lattice. The concept of "vortex lattice melting" has appeared in this approach. In other works (see, for example, [7,8,11]) a revision of the Abrikosov solution is made. Experimental investigation of this problem is connected with investigation of vortex pinning because the pinning appearance is connected with the appearance of the inhomogeneous distribution of the order parameter.

It is well known that the vortex pinning causes non-Ohmic current-voltage characteristics in perpendicular magnetic field. According to the classical work [12], the linear part of the current-voltage characteristic at a large

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current can be described as $V = R_f(I - I_c)$. R_f is the flux flow resistivity. I_c is the dynamic critical current determined by pinning. The experimental investigations show that the current-voltage characteristics become non-Ohmic (I_c becomes nonzero) below H_{c2} both in bulk superconductors [5,6,10,13] and in thin films [14]. In Refs. [13,14] this qualitative change is interpreted as a vortex lattice melting whereas in [5,15] it is interpreted as a transition from the normal state into the Abrikosov vortex state. But the vortex liquid does not represent a new genuine thermodynamic phase different from the normal state [3]. Therefore these two interpretations coincide.

The position and the width of this transition in bulk superconductors differ from those in thin films. In bulk conventional superconductors the current-voltage characteristics become non-Ohmic at some percent below H_{c2} only [6,10], whereas in thin films the position of this transition ("melting") depends on the film thickness [14] and may be below $0.5H_{c2}$ [14]. This difference agrees with the difference of the influence of fluctuation on three- and two-dimensional superconductors with real size which is predicted by theory [16–18].

It was shown [15] that in a bulk superconductor with weak pinning the width of the transition connected with pinning appearance (melting transition) is very small, much smaller than the width of the specific heat transition [9], the magnetization transition [10], and the resistive transition in parallel magnetic field [5], which are connected with the change of the spatial average value of the order parameter. Therefore in [11] the transition connected with the appearance of non-Ohmic current-voltage characteristics (with pinning appearance) was called a narrow transition, whereas the transition connected with the change of the spatial average value of the order parameter was called wide transition. The intrinsic width of the narrow transition has not been determined. It was determined only in [15] that the narrow transition of the most homogeneous sample is more than 10 times narrower than the intrinsic wide transition. It was shown in [6] also that not only does the pinning appear (the I_c value becomes nonzero) but also the flux flow resistivity R_f decreases sharply at the narrow transition of bulk superconductors (see [5] also). The resistivity dependences of thin films do not have sharp features and are smooth at the pinning appearance (at melting) [14].

In the present work we investigated thin films. Thin films were studied before in some works [14,19]. But our investigations have shown that the position of the melting transition is not universal for different films and depends on the amount of pinning centers in them. Therefore we wanted to produce films with the smallest amount of pinning centers. The results of the investigation of these films are presented here. Following [14] and [15] we will determine the transition (melting [14] or transition into Abrikosov state [15]) position as the point at which the current-voltage characteristics in a perpendicular magnetic field change qualitatively (become Ohmic on increasing the magnetic field and become non-Ohmic on decreasing it). It is obvious that this change of current-voltage characteristics is caused by the pinning appearance (disappearance). Therefore we will connect this transition with the pinning (I_c) appearance (disappearance) also.

Nb, NbN, PbBi, Sn, and NbO_x films produced by magnetron sputtering, pulse laser deposition and electron beam evaporation were examined. All the films, except some amorphous NbO_x films, did not have enough small vortex pinning and therefore are not suitable for our purpose. For this reason we mainly studied the NbO_x films.

The NbO_x films were produced by magnetron sputtering of Nb in an atmosphere of argon and oxygen. The critical temperature T_c of the films used is equal to 2.37 K and $dH_{c2}/dT = -22$ kOe/K. The film thickness $d =$ 20 nm. The normal resistivity $\rho_n = 99\Omega/\square$. The temperature dependence of normal resistivity is very weak, $1/\rho_n|d\rho_n/dT| < 0.0002$ in the region 20-40 K, where superconducting fluctuation is small. The resistivity increases with decreasing temperature. This change can be connected with weak localization. A magnetic field up to 50 kOe produced by a superconducting solenoid was measured with relative error 0.0005. The resistivity was measured in perpendicular magnetic field, with a relative error 0.0001. The 0.01 error in the measurement of the specific resistivity was due to the inaccurate determination of the geometric dimensions of the film structure. The temperature was measured with a relative error 0.001.

The measurement showed that the resistive transition of NbO_x films broadens in a magnetic film as well as that of the HTSC's resistive transition (Fig. 1). The paraconductivity $\Delta\sigma = \sigma - \sigma_n$ dependences above H_{c2} in the linear approximation region are well described by the Ami-Maki theory [20] adapted to a two-dimensional superconductor (Fig. 2). The Maki-Thompson contributions are partly suppressed. The normal conductivity value σ_n was determined from extrapolation of its high temperature dependence, and it is not a fit parameter. Therefore the single fit parameter is the H_{c2} value. The temperature dependence of the fitted H_{c2} values agree with the Maki theoretical dependence [21]. Consequently we have one fit parameter, H_{c2} ($T = 0$), for all paraconductivity dependences. The discrepancy between experimental and Ami-Maki dependences near T_{c2} is connected with the invalidity of the linear approximation in the critical region. The calculation of the fluctuation interaction in the Hartree approximation removes this discrepancy (Fig. 2). For this calculation the Ginzburg number $D = 2\pi k_B T_c/H_c^2(0)d\xi^2(0)$ was used as a fit parameter. The only parameter which was not determined independently is a thermodynamic critical field $H_c(0) = -T_c(dH_c/dT)_{T=T_c}$. The fit value of $-(dH_c/dT)_{T=T_c} =$ 300 Oe/K. This is not far from the value for pure Nb of 472 Oe/K.

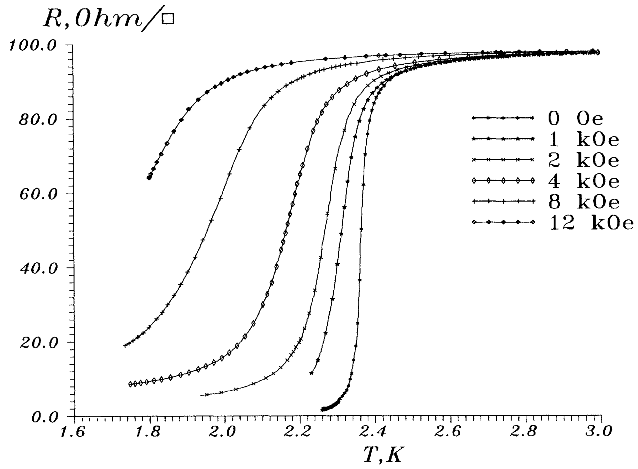

FIG. 1. Resistive transitions of amorphous NbO_x film in different perpendicular magnetic fields. The film thickness $d = 20$ nm.

The paraconductivity investigations show that the amorphous NbO_x films studied are conventional homogeneous two-dimensional type-II superconductors. But the narrow transition that was observed near H_{c2} in bulk type-II superconductors [5,15], or the melting transition that was observed in films [14,19], are not observed in these films. The current-voltage characteristics remain Ohmic down to very low magnetic field (Fig. 3). The resistivity value decreases gradually with decreasing magnetic field value (Fig. 3). At low magnetic field it is close to the flux flow resistivity value (Fig. 3) [22]. The resistivity of a 10 μm width strip at $T = 1.6$ K is equal to zero up to a current value of 10 mA in zero magnetic field and is not equal to zero already at current value 1 nA in a low magnetic field of 100 Oe.

The absence of a nondissipative current, $I_c = 0$, and a resistivity value which is close to the flux flow resistivity value, $R_f/R_n = 0.25H/H_{c2}$, in a low magnetic field are obviously connected with the absence of vortex pinning. It should be noted that the absence of nondissipative current can be connected not only with the absence of pinning but also with flux creep, particularly vortex lattice motion and so on. But in these cases the resistivity value differs from the flux flow resistivity value. This situation was observed earlier in [23] where the resistivity is more than 3 orders of magnitude less than flux flow resistivity, and in other works. Therefore we may say that the pinning absence up to a magnetic field much lower than H_{c2} is observed first in our work.

As was written above, in thin films the pinning disappears (melting transition occurs) not near H_{c2} (as takes place in bulk superconductors [6,10]) but markedly below H_{c2} (at $H = 0.3H_{c2}$ for the film thickness 18 nm and $T/T_c = 0.67$ [14]). Our investigations show that there are films in which the pinning does not appear down to H much lower than the H at which the melting transition was observed in [14] (down to $H = 0.1$ kOe $= 0.006H_{c2}$ for film thickness 20 nm and $T/T_c = 0.67$; see the insertion in Fig. 3). This means that the melting transition in our films can occur below $0.006H_{c2}$ (at $T/T_c = 0.67$) only. Consequently the position of the pinning appearance (disappearance) is not universal for different films. Therefore the theory of vortex lattice melting, used in [14,19], is not valid there. The melting position depends on the amount of pinning centers. The possible influence of pinning centers on the fluctuation value was mentioned in [17].

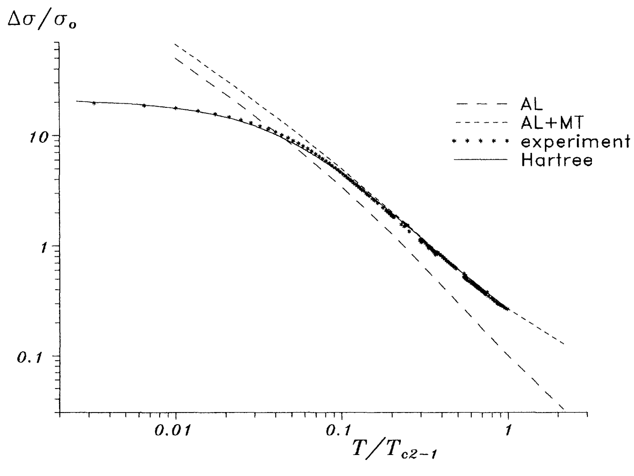

FIG. 2. Paraconductivity $\Delta\sigma/\sigma_0$ dependences on $T/T_{c2} - 1$ for NbO_x film with $d = 20$ nm in perpendicular magnetic field 12 kOe. The theoretical dependences for the Aslamasov-Larkin contribution (AL), for the sum of the Aslamasov-Larkin and Maki-Thompson contributions (AL+MT) (linear approximation) and for the Hartree approximation are shown. $\sigma_0 = e^2/\hbar$. The Ginzburg number $D = 0.003$.

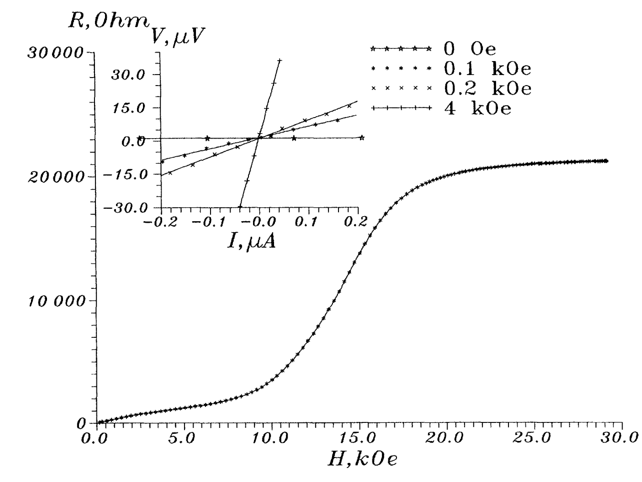

FIG. 3. The magnetic dependence of the resistivity of NbO_x film structure with sizes $d = 20$ nm, width $= 10$ μm and length $= 2.25$ mm. In the inset the current-voltage curves in zero magnetic field and in different magnetic fields are shown. $T = 1.6$ K. $H_{c2} = 16.5$ kOe.

In the papers [14] the resistivity dependences above melting are compared with flux flow resistivity dependences obtained in the mean field approximation. This cannot be right because the fluctuation is big there. It was shown in [5,15,24] that the resistivity dependences of bulk superconductors above melting are described by the paraconductivity theory both above and below H_{c2}. Figure 4 demonstrates that the experimental dependences of two-dimensional superconductors can also be described by paraconductivity theory both above and below H_{c2}. The experimental dependence of $[1 + (\Delta\sigma/\sigma_n)\sqrt{h/t}]^{-1}$ is a universal function of $(t - t_{c2})/\sqrt{ht}$ (Fig. 4), where$t = T/T_c$, $t_{c2} = T_{c2}/T_c$, $h = H/H_{c2}(T = 0)$, and T_{c2} is second critical temperature. This scaling law follows from fluctuation theory [8]. The universal experimental dependence is close to the theoretical paraconductivity dependence obtained in the Hartree approximation (Fig. 4).

Thus the experimental dependences are described by the same paraconductivity dependence both above and below H_{c2}. This confirms the opinion [8,11,18] that the second critical field line $H_{c2}(T)$ marks only a crossover from the normal state to a strongly fluctuating superconducting state with no real phase transition [3]. As was written above, the real phase transition in the Abrikosov vortex lattice state (melting transition) is connected now with qualitative changes of the resistive properties in a perpendicular magnetic field [5,13–15,19]. Therefore the absence of qualitative changes of the resistive properties (the current-voltage characteristics remain Ohmic, $V = R_f I$, up to $0.006H_{c2}$, see the inset in Fig. 3) may be interpreted as the absence of the transition into the Abrikosov vortex lattice state of two-dimensional superconductors with a small amount of pinning centers down to magnetic fields hundreds of times smaller than the second critical field.

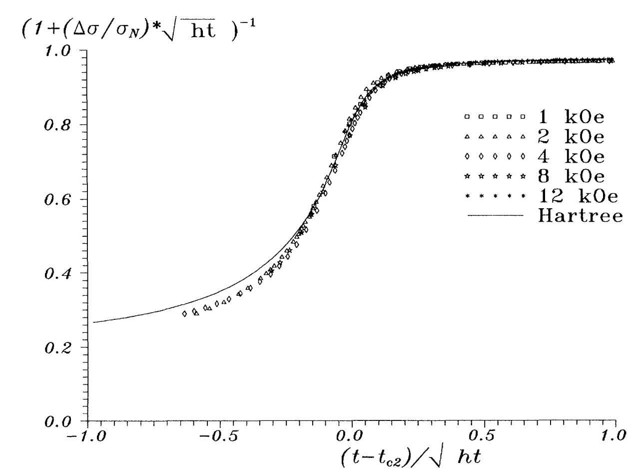

FIG. 4. The $[1 + (\Delta\sigma/\sigma_N\sqrt{ht})]$ versus $(t - t_{c2})/\sqrt{ht}$ dependences in different magnetic fields. The line denotes the theoretical dependences of paraconductivity obtained by the calculation of the fluctuation interaction in the Hartree approximation.

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