Destruction of the phase coherence by the magnetic field in the fluctuation region of thin superconducting film.

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Reduction of the gradient of current density is observed near $T_c$ in thin superconducting films. This effect is explained by the influence of fluctuation superconductivity on the current density distribution. The observed suppression of this effect by low magnetic field is explained by the destruction of phase coherence by magnetic field. The current density distribution in high magnetic field does not differ from that in the normal state down to low temperature ($T < T_{c2}$). This is interpreted as evidence that the superconducting state without pinning below $H_{c2}$ is not a vortex liquid but a state without the phase coherence.

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The superconductivity is a macroscopic quantum effect. Phase $\phi$ of wave function $\Psi = |\Psi|\exp(i\phi)$ of superconducting electrons can cohere all over volume of a superconductor. Quantization of a magnetic flux $\Phi$ and the Meissner effect are consequences of the phase coherence. According to the relation for supercurrent (see for example)

$$j = \frac{\hbar n_s}{4\pi m} \left( \frac{d\phi}{dr} - \frac{4\pi e}{\hbar c} A \right) = \frac{1}{\lambda_L^2} \left( \frac{\Phi_0}{2\pi} \frac{d\phi}{dr} - A \right)$$

the magnetic flux, $\Phi$, contained within a closed path of integration must be equal $\Phi = \Phi_0 n$ because the integral of $d\phi/dr$ along the closed path must be equal $n2\pi$. Here $\lambda_L = (\hbar c/e^2n_s)^{0.5}$ is the London penetration depth; $n_s$ is the superconducting electron density; $\Phi_0 = \hbar c/2e$ is the flux quanta; $n$ is an integer. $\Phi$ must be equal zero in the absence of singularity (nonsuperconducting inclusion) within the closed path of integration because in this case the closed path can be tightened to zero while remaining inside superconducting region. Thus, the magnetic flux cannot be within a superconducting region with phase coherence and without singularities. And this is the cause of the Meissner effect.

Therefore, magnetic field can penetrate into a superconductor only if: 1) superconductivity is destroyed, or 2) singularities appear, or 3) the phase coherence is absent. The first case is observed in type I superconductor. The second case is observed in the Abrikosov state of type II superconductor. The singularities are the Abrikosov vorteces in this case. These two cases are widely known. The third case is not so well known. It is observed in fluctuation superconductivity regions, for example above the second critical field, $H_{c2}$, in type II superconductors.

Zero electrical resistance, the main property of superconductors, can exist only in states with a long range phase coherence. In a state without the phase coherence superconducting fluctuations increase the electrical conductivity (this excess conductivity is called paraconductivity) whereas resistance remains non-zero.

According to the Josephson relation the electrical voltage

$$V = \frac{\hbar}{4\pi e} \frac{d\phi}{dt}$$

in states with the long range phase coherence. Here $V$ is a voltage between two points; $\phi$ is a phase difference between these points. The phase difference changes in time in the Abrikosov state if the vorteces flow. The resistance caused by the vortex flow is called flux flow resistance. This name is no quite right because a magnetic flux induced by an external magnet does not move in a superconductor.

The vortex flow is caused by an electrical current. A flow velocity in real samples depends not only on a current value but also on a pinning force. The vortex can not flow at a current lesser than a critical current. The resistance equal zero in this case. The pinning effect may be in the state with the phase coherence only. Therefore it may be considered as a consequence of the phase coherence.

According to the Abrikosov solution obtained in the mean-field approximation the long range phase coherence appears at mean-field transition point, $H_{c2}$. But the second critical field is not a critical point in the fluctuation theory. In the consequence of the fluctuation the pinning appears below $H_{c2}$. It was shown in work that the pinning appearance in bulk superconductor is a narrow transition. This transition was interpreted in work as a transition from a fluctuation state, as the state with superconducting electrons but without the phase coherence, into the Abrikosov state, as the state with the long range phase coherence. The position of this transition was denoted as $H_{c4}$ in work.

The result of was repeated at investigations of $YBa_2Cu_3O_{7-x}$. But the absence of the pinning in a substantial range of temperature and magnetic field below $H_{c2}$ in high-Tc superconductor was interpreted as a consequence of the vortex lattice melting. This interpretation differs from the one proposed in. The state without pinning is considered as a vortex liquid in this interpretation. The vortex liquid is a state with the phase coherence because the vorteces are singularities in...
superconducting state with the phase coherence. And singularities can not exist without medium.

The resistance in the vortex liquid is caused by the vortex flow as well as in the Abrikosov state. Therefore some difference of resistive properties of the vortex liquid and of the state without the phase coherence may be expected. Nonlocal resistivity in the vortex liquid is predicted in paper [12]. The nonlocal resistivity is considered as a consequence of the viscosity and the incompressibility of the vortex liquid in [2]. The nonlocal resistivity in the vortex liquid may be considered also as a consequence of the phase coherence because the viscosity of the vortex liquid as well as the vortexes can not exist without the phase coherence.

The nonlocal resistivity considered in [12] may be interpreted as a reduction of a gradient of the current density in a consequence of the viscosity of the vortex liquid. A similar nonlocal resistivity may be observed also in the fluctuation region above $T_c$. According to the relation (1) and the Maxwell equation a superconducting current density within fluctuation superconducting drops which appear near $T_c$ must be constant because size of this drops is smaller than the penetration depth. Therefore a gradient of the current density must decrease near $T_c$. This decreasing can be visible if size of the fluctuation superconducting drops is no much small. It may be within the critical region. The critical region of a bulk superconductor is very narrow. Therefore we use amorphous Nb$_{1-x}$O$_x$ thin films. The critical region of these films is enough wide.

The Nb$_{1-x}$O$_x$ films were produced by magnetron sputtering of Nb in an atmosphere of argon and oxygen. The critical temperature $T_c$ of these films depend on oxygen content. Three films with $x \approx 0.15 - 0.25$ and $T_c = 1.86$ K, 2.46 K and 2.52 K were used in this work. Amorphous Nb$_{1-x}$O$_x$ is a type-II superconductor with big value of the Ginzburg-Landau parameter $\kappa$ and of the normal resistivity, $\rho_n$: $\kappa \approx 50$, $dH_{c2}/dT = -22$ kOe/K, $\rho_n = 200 \mu \Omega \cdot cm$. The temperature dependence of normal resistivity is very weak, $|d\rho_n/dT|/\rho_n < 0.0002 K^{-1}$ 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. The used films have very weak pinning. It was shown in work [3] that the resistive dependencies of these films are described by paraconductivity theory in a wide region both above and below $H_{c2}$.

The film structure used is shown schematically in Fig. 1. This structure was obtained by electron lithography and ion-beam etching. The width of the strip in which current flows is equal approximately 4$\mu$m. The branch width is equal approximately 8$\mu$m. The distance between potential contacts 1-1 is equal approximately 6$\mu$m. The distance between potential contacts 3 and 4 is 4$\mu$m, between 3 and 2 is 8$\mu$m. The width of the strip of the potential contacts is 0.2$\mu$m. The film thickness $d = 20$ nm.

The voltage was measured with a relative error 0.0001. The temperature was measured with a relative error 0.001. A magnetic field produced by a superconducting solenoid was perpendicular to a film plane.

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Results obtained by investigation of three samples with $T_c = 1.86$ K, 2.46 K and 2.52 K are similar. The temperature dependencies of the relation $v_{ii} = V_{ii}(T)/V_{ii,n}$ on contacts 1-1, 4-4, 2-2 and 3-3 of the sample with $T_c = 1.86$ K in zero magnetic field are shown on figure 1. $V_{ii}(T)$ is voltage on contacts 1-1, 4-4, 2-2 and 3-3 at temperature $T$ and $V_{ii,n}$ is the same at $T = 4.2$ K where superconducting fluctuation is very small. The relations voltage on the contacts to the transport current value, $I$, in the normal state are $V_{11,n}/I = 146 \Omega$; $V_{33,n}/I = 185 \Omega$; $V_{44,n}/I = 111 \Omega$; $V_{22,n}/I = 60 \Omega$. The $v_{ii}(T)$ do not depend on the transport current value if I does not heat appreciably the film. The overheating of the region between contacts 1-1 determined by displacement of the resistive transition at relatively large current is equal 0.008 K/(10 $\mu$A)$^2$. The overheating of the regions between other contacts is smaller. The dependencies on Fig.1 are obtained at $I = 2 \mu$A. The overheating at this current value does not exceed 0.0005 K.

Because the film is very homogeneous (critical temperature difference of regions between contacts 2-2, 3-3, 4-4 and 1-1 does not exceed 0.001 K) the resistivity, $\rho$, between all contacts must be equal. Consequently the observed difference of the $v_{22}$, $v_{44}$, $v_{33}$ and $v_{11}$ values is caused by a change of the current density, $j$, between contacts 2-2, 3-3, 4-4 near $T_c$. It is obvious that $j$ between contacts 1-1 does not change if I is constant. The $v_{11}(T, H)$ dependencies repeat the resistivity dependencies obtained before [3]. These dependencies are described by paraconductivity theory [3]. $1/v_{11} - 1 = \rho_n/\rho(T) - 1 = \sigma_T/\rho_n$. If we will introduce an average current density between the potential
contacts, \( j_{ii} \), we may write \( V_{ii} = j_{ii} \rho_{ii}. \) \( l_{ii} \) is a distance between potential contacts i-i. Then \( v_{ii} = V_{ii}(T)/V_{ii,n} = j_{ii}(T)/j_{ii,n} \rho_{ii}. \) Where \( j_{ii,n} \) is the average current density between the contacts i-i in the normal state without superconducting fluctuation (at \( T = 4.2 \) K). Because \( j_{11} \) is not changed, \( v_{ii}/v_{11} = j_{ii}(T)/j_{ii,n}. \) We may estimate a value of an additional current between contacts i-i near the superconducting transition from above relation. \( \Delta j_{ii} = j_{ii}(T) - j_{ii,n} = j_{ii,n}(v_{ii}/v_{11} - 1). \)

![FIG. 2. Temperature dependencies of voltage relation on potential contacts 4-4, V_{44}/V_{44,n}, at different values of perpendicular magnetic field. The upper (at \( T = 1.87 \) K) curve H = 0, the lower (at \( T = 1.87 \) K) curve H = 500 Oe.](image)

It is obvious that the difference of the values \( V_{33,n}/I; \) \( V_{44,n}/I; \) \( V_{22,n}/I \) is caused first of all by a difference of the current density between these contacts, \( j_{22,n} < j_{44,n} < j_{33,n} \), because distances between these potential contacts are approximately equal. Near \( T_c, \) \( v_{44}/v_{11} - 1 > 0, \) \( v_{22}/v_{11} - 1 > 0 \) and \( v_{33}/v_{11} - 1 < 0 \) (Fig.1). This means that the current density between the different contacts draw nearer close by \( T_c. \) According to figure 1 \( v_{22}/v_{11} - 1 > v_{44}/v_{11} - 1. \) This means that the additional current value decreases with removal from the I strip more slowly than \( j_{ii,n}, v_{44}/v_{11} - 1 \) and \( v_{22}/v_{11} - 1 \) increases with approach to the \( T_c \) more sharply than paraconductivity value and is observed near \( T_c = 1.84 \) K only (Fig.1). The \( T_c \) value was determined from paraconductivity dependence in linear approximation region with exactness 0.01 K.

Thus, the reduction of the gradient of the current density near \( T_c \) is observed indeed. This effect was observed in all investigated samples and therefore can not be connected with sample inhomogeneity. Following to [2] we will call this effect as the nonlocal resistivity. The nonlocal resistivity can be useful for investigation of an action of a magnetic field on the superconducting drops. Two possibility can be in a enough high magnetic field: 1) the Abrikosov vorticees appear within the superconducting drops; 2) the magnetic field destroys the phase coherence. In the first case the observed effect must not decrease in the magnetic field because the relation (1) is linear.

![FIG. 3. Temperature dependencies of voltage relation on potential contacts 4-4, V_{44}/V_{44,n}, and 1-1, V_{11}/V_{11,n}, in the perpendicular magnetic field H = 0.5 kOe and H = 2 kOe. I = 2 \( \mu \)A.](image)

Our investigations show that a magnetic field suppresses the nonlocal resistivity much more strongly than the paraconductivity value (Fig.2). The nonlocal resistivity begins to decrease in very low magnetic field (Fig.2), decreases in some times at \( H = 0.5 \) kOe and disappears in higher magnetic field (fig.3). The paraconductivity value changes very little in these values of the magnetic field (see Fig.2). The observed small change of the paraconductivity value is consistent with small change of the mean-field critical temperature, \( T_{c2} - T_c = H/(dH_{c2}/dT). \) At \( H = 20 \) Oe, \( T_{c2} - T_c \approx -0.001 \) K; at \( H = 0.5 \) kOe, \( T_{c2} - T_c \approx -0.02 \) K.

The magnetic field can not act on superconducting drops with size smaller than \( (\Phi_0/H)^{0.5}. \) Consequently the superconducting drops with size \( > (\Phi_0/20 \) Oe\(^{0.5} \approx 1\) \( \mu \)m contribute to the observed effect. But the nonlocal resistivity is observed at \( H = 500 \) Oe. Therefore we can propose that the superconducting drops with size \( < (\Phi_0/500 \) Oe\(^{0.5} \approx 0.2\) \( \mu \)m contribute to the effect also.

Thus, the magnetic field destroys the phase coherence in the fluctuation superconducting drops first of all. The nonlocal resistivity predicted for the vortex liquid in work [2] is not observed in high magnetic field up to low temperature. This means that a state without pinning is no vortex liquid but is the state with superconducting electrons but without the phase coherence. Consequently the transition observed in [11] is not the vortex lattice melting but is the phase coherence disappearance.

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