MAGNETIC INDUCTION INFLUENCE ON KOSTERLITZ-THOULESS TRANSITION IN LAYERED SUPERCONDUCTORS

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An influence of external magnetic field on the resistive transition in the Josephson decoupled layered superconductor is investigated. The critical induction B_{cr} quite small with respect to lower critical field H_{c1} is obtained. At small induction $B < B_{cr}$, the type two resistive transition is occurred as Kosterlitz-Thouless one. At large induction $B > B_{cr}$, the kind of phase transition is changed from second order to first one and the vortex pair dissociation has a hysteretic behavior in some temperature interval lying below and close to Kosterlitz-Thouless temperature T_{KT} . The lowest boundary of this interval decreases by induction increasing and coincides with temperature of resistive transition.

The resistivity appearance in Josephson-decoupled layered superconductors is stipulated by two-dimensional (2D) vortex pair dissociation. Resistivity transition is occurred at the temperature

$$T_{KT} = \frac{\phi_o^2}{16\pi^2\Lambda(T_{KT})}. \quad (1)$$

under zero magnetic induction and is fully described in framework of Kosterlitz-Thouless model as a second order phase transition [1-3]. Here ϕ_o is flux quantum, $\Lambda = 2\lambda/d$, λ is magnetic penetration depth, d is interlayer distance. Resent experiments studied an magnetic field influence on this transition have shown a set of unusual properties of one. The temperature of resistive transition T^* coincides with T_{KT} by external field increasing from zero up to some critical value B_{cr} and T^* begins to slowly decrease in field exceeding B_{cr} [4]. The rate of reduction of T (B) noticeably increases by growth of insulating layers thickness in superconductor [5]. In paper [6] there was find hysteretic behavior of resistive transition as well as first order phase transition. The hysteresis width in temperature increases with applied field. In this paper I explain all this peculiarities in framework of one Kosterlitz - Thouless model by taking into consideration of magnetic field penetrated into layered superconductor as a flux line lattice.

We consider a system of identical superconducting layers with spacing d between them and layer thickness much less then d and penetration depth λ. The distribution of the vector potential $\mathbf{A}(\mathbf{x})$ throughout all space and screening currents in superconducting k-th layer we will describe within the Lawrence - Doniach model by zero Josephson coupling :

$$curlcurl\mathbf{A}(\mathbf{x}) = \frac{2}{\Lambda}\left[\frac{\phi_o}{2\pi}\sum_{i,k}\nabla\theta(\mathbf{x}-\mathbf{x}^o_{i,k}) - \mathbf{A}(\mathbf{x})\right]\delta(x_3 - kd), \quad (2)$$

Here the phase gradient $\nabla\theta(\mathbf{x}-\mathbf{x}^o_{i,k})$ is a magnetic field source of 2D vortex placed in k-th layer. The 2D vortices we divided on two main part:

$$\sum_{i,k} \nabla\theta(\mathbf{x}-\mathbf{x}^o_{i,k}) = \sum_{\mathbf{R}} \nabla\theta(\mathbf{x}-\mathbf{R}) + \sum_k \int d^2\mathbf{x}'[n^+_k(\mathbf{x}') - n^-_k(\mathbf{x}')]\nabla\theta(\mathbf{x}-\mathbf{x}'). \quad (3)$$

One of them forms flux line lattice,i.e. the stacks of 2D vortices whose centers $\mathbf{R}$ are the same in each of layers. The second one is a gas of free excitations. Averaging densities of positive excitations $n^+_k(\mathbf{x})$ and negative one $n^-_k(\mathbf{x})$ coincide each with other that follows from the condition of vortex-antivortex pair dissociation. Interaction of free excitations with the flux lines leads to the space distribution of gas density :

$$n^{\pm}(\mathbf{x}) = n^{\pm}_o(\mathbf{x}') exp(-\beta U(\mathbf{x}-\mathbf{x}')), \quad (4)$$

$$\beta = \frac{1}{T}.$$

$U(\mathbf{x})$ is the energy of interaction of the 2D excitation and flux line lattice. To deduce n^-_o we consider an extreme case of 2D antivortex placing on 3D vortex axis. The 2D antivortex and 2D vortex from stack of ones annihilate and their place is occupied by one pair from free dipole gas, whose density is equal to n_{dip}. Thus,

$$n^-_o = n_{dip} \exp(\mp\beta U(0) - \beta F_o). \quad (5)$$

Here F_o is the 2D vortex self energy, $U(0)$ is the energy of one 3D vortex link interaction with the all other flux lines of lattice.

The free excitation density we write in form

$$n^-(\mathbf{x}) = n^-_o \exp(\beta < U >) \exp(\beta[U(\mathbf{x}) - < U >]).$$

For the linearization of $n^-(x)$ we expand the second exponent only, because the alone value $\beta U(\mathbf{x})$ can be in excess of unit in case of dense flux line lattice.

The equality of full numbers of free 2D vortices and antivortices from excitation gas leads to the condition

$$n^+_o \exp(-\beta < U >) = n^-_o \exp(\beta < U >) \equiv n_o.$$

The main results, obtained by solving of linearizing Eqs.(2-4) following to the paper [7], are the self energy of one 2D excitation,

$$F_o = \frac{\phi_o^2}{8\pi^2\Lambda} K_o(\frac{\xi}{l}), \qquad l(n_o) = \frac{2\pi\Lambda}{n_o\beta\phi_o^2},$$

and the equation in unknown equilibrium "density" n_o of excitations,

$$n_o = n_{dip}\Big(1 + \frac{b}{1+(\lambda/l)^2}\Big)^{\beta T_{KT}} \exp\Big(-2\beta T_{KT} K_o(\frac{\xi}{l})\Big). \quad (6)$$

Here dimensionless induction is

$$b = B\Big(\frac{4\pi\lambda^2}{\phi_o}\Big)\frac{2\sqrt{3}}{\pi}.$$

It is clear seen that by finite value $l(n_o)$ a logarithmic singularity of F_o is absent and self energy of 2D vortex in excitation gas is finite.

Let us solve the Eq.(6). One of solutions of Eq.(6) is $n_o = 0$ that is valid within full temperature region. Nonzero solution $n_o(T)$ defines the nonzero resistivity, so temperature minimum at which $n_o \neq 0$ is a resistivity transition one T^* .

In case of zero induction $b = 0$, nonzero density

$$n_o = n_{dip} p^z \ll 1, \tag{7}$$

$$p = n_{dip} \xi^2 2\pi \exp\left(2\gamma \frac{T_{KT}}{T}\right), \qquad z = \frac{T_{KT}}{T - T_{KT}},$$

is appeared at $T > T_{KT}$ only. Here we made assumption $p < 1$ at $T = T_{KT}$. An analysis of all known experiments performing on superlattices and strong anisotropic superconductors confirms this one. However, we note that the value p is very close to the unit [8] and any induction $b \neq 0$ leads to increasing of this value. It is worth noticing that a rather small critical value of induction $b_{cr} \ll 1$ at which $p = 1$ exists and we get $p > 1$ at $b > b_{cr}$.

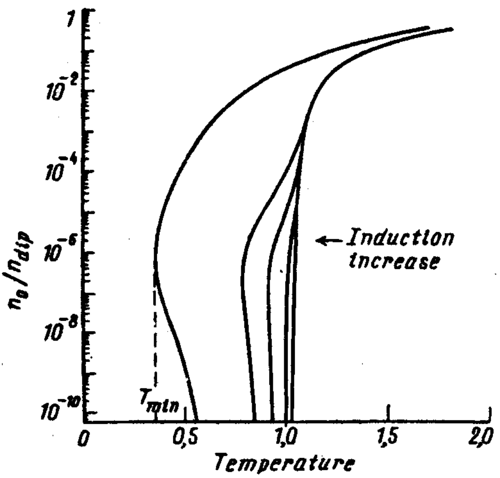

Рис.1

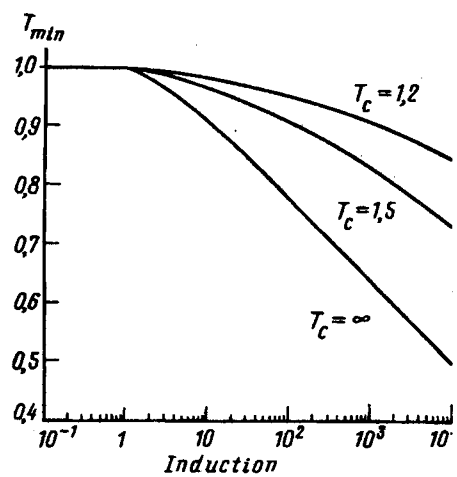

Рис.2

Fig.1. Temperature dependence of the free excitation density for $T_{KT} = 1$, $b_{cr} = 1$, $\kappa = 200$. $b = 0; 1; 10; 10; 10$.

Fig.2. Dependence of low limit T_{min} of hysteresis region of $n_o(T)$ on induction for $T_{KT} = 1$, $b_{cr} = 1$, $\kappa = 200$.

Solution $n_o(T)$ has one significant peculiarity at $b > b_{cr}$, namely nonsingle–valued dependence on temperature. Numerical solutions of Eq.(7) at different inductions are shown on Fig.1. It is seen that in case of $b > b_{cr} = 1$ a nonzero density n_o exists below critical temperature $T_{KT} = 1$. There is a lowest value T_{min} on temperature scale at which $n_o(T) \neq 0$. The dependence $T_{min}(b)$ we demonstrate on Fig.2. The lowest curved line with label $T = \infty$ is the solution of Eq.(7) with constant values λ and ξ. This condition is valid in case of very small T_{KT} with respect to superconducting transition temperature T_c . A difference between T_c and T_{KT} of the layered superconductor is roughly equal to several degrees and we have to take into account the dependence of λ and ξ on T. On Fig.2 we show too the dependencies $T_{min}(b)$ for two small values T_c slightly exceeded T_{KT}.

The discovery of critical induction value B_{cr} at which a type of phase transition is changed is the main result of my paper. At small induction $B < B_{cr}$ the 2D pair dissociation is occurred following to KT scenario. In this case free excitations are absent by temperature increasing up to T_{KT} and their density slowly increases at temperature exceeding T_{KT}. Another picture can be observed at large induction $B > B_{cr}$ when disruption of vortex pairs is first order phase transition. Some interval of temperature

$$[T_{min}, T_{KT}], \tag{8}$$

in which a function $n_o(T)$ is nonsingle-valued is appeared. It is easily to understand that the two solutions, namely $n_o(T) = 0$ and maximum value of n_o , correspond to local minimum of free energy in hysteretic region (8), and middle brunch $n_o(T)$ describes a potential wall between them. We take note of stable solutions $n_o(T)$ come not into contact each with other and transition from one solution to another must be accomplished by jump.

A hysteretic behavior of $n_o(T)$ consisting jumps of density is a more probable one by temperature cycling. The resistivity of the superconductor must abruptly increase at free excitation appearance. So, hysteresis of $n_o(T)$ can be displayed in irreversible and step like behavior of the current–voltage characteristic. At the same time, induction increasing leads to expansion of temperature range (8) where resistivity is irreversible. Analogous dependence $R(T)$ have been described in paper [6]. In this work a nonlinear widening of hysteretic temperature interval by induction increasing has been revealed that is in agreement to numerical solution shown on Fig.2. Besides, experimentally discovered hysteretic interval is very narrow, less then 0.1 degree. Such narrow range (8) we can obtain from the theory at T_{KT} and T_c distinguishing each from other on 1 degree or so, that is confirmed by numerous experiments.

For the first order phase transition a sample dividing on domains is more typical one with respect to uniform phase transition. In our case domains are the regions with $n_o = 0$ and nonzero n_o . The domain existence is possible only in temperature region (8). Relative volume of domain with $n_o \neq 0$ increases from zero at $T = T_{KT}$ to unit at $T = T_{KT}$ by temperature increasing. An appearance of resistivity in sample divided on domains should be occurred at $T \sim T_{min}(B)$. A temperature decreasing of resistive transition by induction increasing is strong experimental fact (see, for example, [4,5]) and qualitatively coincides to obtained dependence $T_{min}(B)$. It should be specially noted the paper [4] where resistive transition has been studied at small inductions and it has been shown that T_{min} deviates from T_{KT} at $B > 15$ Oe. I believe that future experiments will confirmed my model in detail.

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