CURRENT-PHASE RELATION IN LAYERED CUPRATES

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The influence of interlayer tunneling in layered superconducting (SC) medium on the intralayer SC is shown to be essential in strongly anisotropic cuprates. Josephson-like transverse current is found to be some universal function of the phase difference Ω between adjacent layers while simple Josephson sinusoidal dependence on Ω is valid only at rather low temperatures $T \ll T_{cr}$, 3D-2D crossover temperature.

In usual Josephson junction formed by bulk banks SC order pa- rameter, $|\psi|$, is weakly perturbed by tunneling current and deeply in banks may be taken equal to value $|\psi_0|$ of separate bulk sample. In layered compound with atomic thickness of layers $d \cong \xi_\perp$, SC correlation length in normal to layer z-direction (as in crystal HTSC),both effects (SC and tunneling) are of the same dimensionality and may essentially influence one another.If in bulk case the perturbation of order parameter modulus $|\psi|$ by tunneling current j_z may be neglected, in the layered system on the contrary j_z may essentially reduce the density of SC pairs, n_s, in analogy with current flowing through the thin SC film or wire [1]. In this work the set of variational equations for layered SC is studied including together with vector potential, A, and order parameter phase, φ, the uniform density $n_s = |\psi|^2$, as variational variable too. An optimal current-dependent value of n_s is found in array of $S-I-S$-junctions. It is supposed that correlation between phases φ_n, φ_{n+1} of order parameters ψ_n, ψ_{n+1} of adjacent SC layers is controlled by uniform SC current flowing in z-direction.

Since the value of Josephson current is proportional to n_s the persistent current in such a structure exhibits nontrivial dependence on temperature and gauge-invariant phase difference

$$\Omega_n = \varphi_{n+1} - \varphi_n - \int_{z_n}^{z_{n+1}} dz A_z \quad (\hbar = 1). \tag{1}$$

Uniform suppression of order parameter when current is applied and uniform phase difference between adjacent layers is establi- shed to reduce critical current density with respect to Josephson critical current $j_c = 2eE_J(T)$, $E_J(T)$ is energy of Josephson coupling of layers. In the most anisotropic Bi- and Tl-based HTSC where fluctuation region width $\tau_f \gg \tau_{cr}$ [2] ($\tau_{cr} = 1 - T_{cr}/T_{c0}$, T_{c0} is mean field transition temperature) suppression of interlayer coupling E_J due to fluctuations may reduce j_c more essentially then mentioned above mechanism. But in less anisotropic single crystals of 1-2-3 compounds where $\tau_f \ll \tau_{cr}$ [2] fluctuation correction is of order of τ_{KT}/τ ($\tau = 1 - T/T_{c0}$, $\tau_{KT} < \tau_f$ is dimensionless Kosterlitz-Thouless temperature of single layer) and may be neglected at $\tau > \tau_{cr}$. Then at temperatures $\tau \geq \tau_{cr}$ linear dependence of Josephson critical current $j_c \propto \tau$ is substituted by $j_c \propto \tau(1 - \tau_{cr}/2\tau)$.

Quasi-2D behavior of HTSC is usually described by Ginzburg - Landau free energy functional in Lawrence - Doniach form (GL-LD model) that reads [3]

$$F = d\sum_n \int d^2\rho \left\{ \alpha n_s + \beta n_s^2 + \frac{n_s}{4m}\left[|\bar{\nabla}_{\parallel}\varphi_n - \frac{2e}{c}\mathbf{A}_{\parallel}|^2 + \frac{2m}{Md^2}(1-\cos(\Omega_n))\right]\right\} + \int \frac{h^2 dV}{8\pi} \tag{2}$$

where d is interlayer distance, m and M is effective electron masses in (ab)-plane and z-direction respectively, h is magnetic field. GL-LD-model is valid at temperatures $T < T_{cr}$, where 3D-2D crossover temperature is defined by equality $\xi_{\perp}(T_{cr}) = d/\sqrt{2}$.

$2D$-type vortex fluctuations thermally induced in separate layers lead to the arising of nonuniform phase difference between adjacent layers reducing effectively the interlayer coupling and critical current respectively [4-6]. In layered systems, however, fluctuation width of SC transition is controlled by $\gamma = m/M$, anisotropy parameter, and turns out to be finite on the contrary to $2D$ case. Then, fluctuation mechanism of suppression of transverse critical current $j_{c\perp}$ is essential only in temperature region close to T_{kt}, Kosterlitz - Thouless temperature of separate SC sheet. In low temperature region $\tau \gg \tau_{cr}$, the number of thermally induced $2D$-vortices of Abricosov type as well as Josephson-like vortex loops [5] is exponentially small and may be neglected.

Thus, in strongly anisotropic layered single crystal HTSC (where it is supposed that width of fluctuation region $\tau_f > \tau_{cr}$) out of fluctuation region and in less anisotropic 1-2-3 compounds at $\tau > \tau_{cr}$ the suppression of interlayer critical current may occur only due to decreasing of n_s comparing to $n_{s0} = |\psi_0|^2 = -\alpha/\beta$.

To give prominence to this effect let us suppose for simplicity that j_z is distributed uniformly in (ab)-plane and it is small enough to neglect its self-field. Then omitting in absence of external magnetic field the terms connected with nonuniformity of order parameter in planes one can find that minimum of free energy (2) is delivered by value

$$n_s = n_{s0}[1 - (\xi_{\perp}/d)^2(1 - \cos(\Omega_n)] \tag{3}$$

where Ω_n in adopted conditions is the same for all junctions. At low Ω_n the SC density deviates by value of $\Omega_n^2 \cong j_z^2$ as in thin film (wire) [1]. Variation of energy (2) with respect to A_z [3] yields together with (3)

$$j_z = j_{c0}\left[1 - \frac{\tau_{cr}}{2\tau}(1-\cos(\Omega_n))\right]\sin(\Omega_n), \tag{4}$$

$j_{c0} = (en_{s0}\gamma/2md)$ is value of Josephson critical current of bulk junction.

It is easily seen that maximum value of dependence (4) is achieved at $\Omega < \pi/2$ defined by

$$\cos(\Omega) = [\sqrt{(1-\tau_{cr}/2\tau)^2 + 2(\tau_{cr}/\tau)^2} - (1 - \tau_{cr}/2\tau)](2\tau_{cr}/\tau)^{-1} \tag{5}$$

and may be as small as $j_{z,max}/j_{c0} = 3\sqrt{3}/8$ (at $\cos(\Omega) = 1/2$). In low temperature region $\tau \gg \tau_{cr}$ $\cos(\Omega) \cong \tau_{cr}/2\tau$ and one finds from (4)

$$j_{z,max} = j_{c0}[1 - \tau_{cr}/2\tau]. \tag{6}$$

It should be stressed the universal character of functional dependence (4) that contains no specific parameters of material except for anisotropy-mediated τ_{cr} (constant value j_{c0}, is of course, determined by the material too). The parameter $\tau_{cr}/2\tau$ generally speaking is not small because GL-LD model is valid up to $\tau \cong \tau_{cr}$. In the region $\tau < \tau_{cr}$ the above consideration loses its validity and the crossover to anisotropic 3D low of critical current $j_{c\perp} \propto \tau^{3/2}$ should take place. Thus, the decreasing of critical current (6) may be considered as pre-crossover phenomenon.

Let us note in conclusion that deviation of current-phase relation from simple sinusoidal dependence and violation of linear temperature dependence of Josephson-like critical current may take place also in granular SC medium, such as ceramic HTSC. Provided the intergranular barrier transparency satisfies certain conditions [7] this may occur due to homogeneous suppression of order parameter inside grains by usual depairing process [1] or due to surface influence on density n_s in grains.

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1. J.Bardeen, Rev. Mod. Phys. **34**, 667 (1962).
2. D.I.Glazman and A.E.Koshelev, Sov. Phys. JETP **70**, 774 (1990).
3. W.E.Lawrence and S.Doniach, Proc.12-th Intern. Conf. on Low Temp. Phys., ed. by E.Kanda (Academic Press of Japan, Kyoto, 1971), p.361.
4. H.Weber and H.J.Jensen, Phys. Rev. B**44**, 454 (1991); P.Minnhagen and P.Olsson, Phys. Rev. B**44** 4503 (1991); Ibid. B **45**, 5722 (1992); Phys. Rev. Lett. **67**, 1039 (1991).
5. B.Horovitz, Phys. Rev. Lett. **67** 378 (1991).
6. Yu.A.Genenko and Yu.V.Medvedev, Phys. Lett. A**167**, 427 (1992).
7. M.Yu.Kupriyanov, Pisma v Zh.Eksp.Teor.Fiz. **56**, 414 (1992).