

SOME PROPERTIES OF VORTEX LATTICE IN LAYERED SUPERCONDUCTING STRUCTURES.

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The current increase of interest in study of layered superconductors is related mainly to the fact that some of the high T_c superconductors (e.g., Bi-Ca-Sr-Cu-O) are layered compounds. Besides, the suppression of the order parameter at twinning planes [1] or at planes with oxygen deficiency allows one to consider a superconductor with a regular set of such planes as a system of alternating S and N (or I) layers. We call such systems with the Josephson interaction between S-layers as {S,N} or {S,I} systems (N and I are layers of the normal and insulating phases). The {S,N} or {S,I} systems can be made also artificially [2].

If the applied magnetic field H_e exceeds a threshold value H_{J1} , the Josephson vortices (J-vortices) begin to penetrate into the system. Their centers are placed at the I-layers (for definiteness, we will consider the {S,I} system). At $H_e \gg H_{J1}$ a dense lattice of the J-vortices (J-lattice) is formed in the system. If H_e exceeds a threshold value H_{c1}^* , the Abrikosov vortices (A-vortices) deforming the J-lattice penetrate into the S-layers (H_{c1}^* differs from the lower critical value H_{c1} for a bulk superconductor: $H_{c1}^* > H_{c1} \gg H_{J1}$). In this report some properties of vortex lattices in the {S,I} system will be analyzed; in particular, we will calculate the spectrum of J-lattice oscillations and study the interaction of the A-vortices immersed into the J-lattice.

2. Suppose that one A-vortex is situated at the point (0,0) (see Fig.1), and there is an arbitrary number of the J-vortices in the system. The spatial dependence of the field $H(r)$ directed along the y axis is given by formula [3]

$$H(r) = K_0(r) + (1/2) \sum_m \int \frac{dk}{2\pi} \frac{[\phi'_m(x)]_k}{\rho(k)} \exp(ikx - \rho(k)|z-z_m|) \quad (1)$$

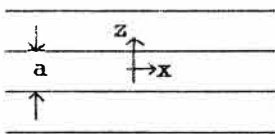


Fig.1

Here magnetic field and length are measured in units $\Phi_0/(2\pi\lambda^2)$ and λ (λ is the London penetration length); $\rho(k) = (1+k^2)^{1/2}$,

$[\phi'_m(x)]_k$ is the Fourier component of the function $\phi'(x) \equiv \partial\phi/\partial x$, ϕ_m is the phase

difference at the I_m -layer. If there are many A-vortices, the MacDonald

function $K_0(r)$ should be replaced for the sum over all A-vortices. From the Josephson and Maxwell equations one can obtain the relation between ϕ_n and the magnetic field in the n-th I-layer, $H_n \equiv H(x, z_n)$,

$$H'_n = (2\lambda_J^2)^{-1} [\sin\phi_n + \tau_n \dot{\phi}_n + \omega_0^{-2} \ddot{\phi}_n] \quad (2)$$

where λ_J is the dimensionless Josephson length, $\tau = \hbar/(2eRj_c)$, $\omega_0^2 = 2ej_c/(\hbar C)$; R, C and j_c are the resistivity, capacitance and critical

current of the Josephson junctions S-I-S (per unit square), $\dot{\phi}_n = \partial\phi_n/\partial t$. Making use of Eqs.(1) and (2), we consider the case when the density of the J-lattice is high. Then, ϕ_n can be represented in the form $\phi_n = Hx + \pi n + \psi_n + \vartheta_n \equiv \phi_n^{(0)} + \vartheta_n$, where $\phi_n^{(0)}$ describes the unperturbed J-lattice in quasistatic approximation, and the phase ϑ_n determines deformations of the J-lattice. The amplitude of the function ψ_n oscillating with period $2\pi/H$ is assumed to be small, and the constant H is related to the field H_e and magnetic induction of the J-lattice, B_J ,

$$H = B_J a = 2 \tanh(a/2) H_e (1 - f), \quad f = (1/2)[2\lambda_J H_e \tanh(a/2)]^{-4} \ll 1, \quad (3)$$

where a is the thickness of the S-layers. Expanding $\sin\phi_n$ in ψ_n and averaging (2) over J-lattice period, one can obtain an equation for ϑ_n ,

$$\lambda_J^2 \sum_m'' \exp[-a|n-m|] = -l_H^{-2} [\sin(\vartheta_{n+1} - \vartheta_n) + \sin(\vartheta_{n-1} - \vartheta_n)] + \tau \dot{\vartheta}_n + \omega_0^{-2} \ddot{\vartheta}_n, \quad (4)$$

which is valid provided

$$(\omega/\omega_0)^2 < l_H^2, \quad 1 \ll l_H^2 / \cosh(a\varphi(H)). \quad (5)$$

Here $l_H = 2\lambda_J H [\sinh(a\varphi(H))/\rho(H)]^{1/2}$ is a rather large length. Eq.(4) describes the dynamics of J-lattice deformations.

3. Making use of eq.(4), we can study of long wave oscillations of the J-lattice ($qa, k \ll 1$). Linearizing eq.(4) for perturbations $\delta\vartheta_n \approx$

$\exp[i\omega t - ikx - iqz]$ (here $z = na$), we get for the spectrum of oscillations $\omega^2 = v_\perp^2 q^2 + v^2 k^2 \tanh^2(a/2) [1 + (qa/2)^2] / [\tanh^2(a/2) + (qa/2)^2] + i\omega(\tau\omega_0)$. (6)

Here $v_\perp = \omega_0 a / l_H$ is the velocity of "magnetic sound" propagating across the layers; $v = \lambda_J \omega_0 / \tanh(a/2)$ is the velocity of oscillations propagating along the layers. In the first case the oscillations are not accompanied by the variations of the J-vortex density; they corresponds to the shear oscillations of a crystal lattice. If $k \ll 1$, (but conditions (5) hold), the propagation velocity of this mode diminishes with H_e like $v_\perp \sim H_e^{-1}$. The oscillations propagating along the layers changes the J-lattice density. The considered oscillations will be weakly damped at frequencies $\omega > \omega_0 \tau$ which are not too high in the case of the {S,I} system at low temperatures when $\tau \sim R^{-1} \sim \exp(-\Delta/T)$.

The J-lattice oscillations can be excited by an external alternating perturbation. For example, in the case of ac current flowing along the layers with frequency $\omega < v/L_x$ (L_x is the sample length along the x axes), the spatial distribution of the current density $j(z)$ will be determined by J-lattice deformations. Then, the microwave absorption as a function of H_e must have sharp peaks when the condition $\omega = v_{\perp} 2\pi n/L_z$ ($n = 1, 2, 3, \dots$) is fulfilled [4]. At $H \ll 1$ the distance between adjacent peaks is nearly constant and equals $\delta H_e \cong (\pi/2)(\omega_0/\omega)a\sqrt{\sinh a}$ $(\lambda_{J_z} \tanh(a/2))^{-1}$. The peaks observed in microwave absorption in Y-Ba-Cu-O single crystals [2,5] seem to be associated just with these resonances.

4. The deformation of the J-lattice may appear also when the A-vortices penetrate into the S-layers. Each A-vortex deforms the J-lattice creating a long-range field, $h_n = (1/2)\sum \partial \vartheta_m / \partial x \exp(-a|n-m|)$, which is negative in some regions and leads to mutual attraction of the A-vortices situated in different S-layers if the distance between them is not too large ($|x_A - x_A'| < l_0$, $l_0 = \lambda_{JH}$) [3]. Thus, if the density of the A-vortices is low (i.e., $0 < H_e - H_{c1}^* < H_{c1}^*$), the A-vortices will line up in chains perpendicular to the layers. From (6) one can obtain an equation for the field of a chain, h_n , the solution of which in the stationary case looks like the z-component of electric field of the 2-dim. dipole the length of which equals the one of the chain. Making use of the corresponding expressions for the thermodynamic potential and for h_n , we can determine the contribution of chains formed by the A-vortices into the magnetic induction B,

$$B(H_e) \approx B_J + B_A, \quad B_A = (2L_A/L_z) \exp(-a/2) (H_e - H_{c1}^*)^{\vartheta} (H_e - H_{c1}^*), \quad (7) \textcircled{*}$$

where $\vartheta(x) = 1$ at $x \geq 1$, L_A is the chain length. With increasing H_e the distance between chains, L , diminishes, and at $L \leq 1$ the A-vortices begin to interact directly. Hence, at $H_e \cong H_r$ the A-vortex lattice is reconstructed from a set of chains into the triangular lattice. The evaluation of H_r gives $H_r - H_{c1}^* \cong \exp(-a/2)(a/2 + \ln l_0)^{-1}$ (here, a is assumed to be large: $a \gg 1$). One can see that it is easier to observe the influence of the J-vortices on the A-vortex lattice in samples with $a \ll 1$.

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