SOME PROPERTIES OF VORTEX LATTICE IN LAYERED SUPERCONDUCTING STRUCTURES.

A.F.VOLKOV
Institute of Radioengineering and Electronics of the Academy of Sciences of the USSR, Marx av. 18, Moscow, USSR

The current increase of interest in study of layered superconductors is related mainly to the fact that some of the high T_c supercoductors (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]

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

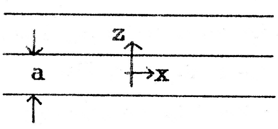

Fig.1

Here magnetic field and length are measured in units $\Phi_o/(2\pi\lambda^2)$ 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

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function $K_o(r)$ 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, $H_n \equiv H(x,z_n)$,

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

were λ_J is the dimensionless Josephson length, $\tau = \hbar/(2eRj_c)$, $\omega_o^2 = 2ej_c/(\hbar C)$; 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 $\phi_n = Hx + \pi n + \psi_n + \vartheta_n \equiv \phi_n^{(o)} + \vartheta_n$, where $\phi_n^{(o)}$ 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,

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

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

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

which is valid provided

$$(\omega/\omega_o)^2 < l_H^2,\ 1 \ll l_H^2/\cosh(a\rho(H)). \qquad (5)$$

Here $l_H = 2\lambda_J H[\sinh(a\rho(H))/\rho(H)]^{1/2}$ 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 ≪ 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

$$\omega^2 = v_\perp^2 q^2 + v^2 k^2 \tanh^2(a/2)[1+(qa/2)^2]/\, [\tanh^2(a/2)+(qa/2)^2] + i\omega(\tau\omega_o). \qquad (6)$$

Here $v_\perp = \omega_o a/l_H$ is the velocity of "magnetic sound" propagating across the layers; $v = \lambda_J\omega_o/\tanh(a/2)$ 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 crystall lattice. If $H<1$, (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 $\omega > \omega_o\tau$ 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...) is fulfilled [4]. At $H\!<\!1$ the distance between adjacent peaks is nearly constant and equals $\delta H_e \cong (\pi/2)(\omega_o/\omega)a\sqrt{\sinh a}$ $(\lambda_J L_z \tanh(a/2))^{-1}$. The peaks observed in microwave absorption in Y-Ba-Cu-O single crystalls [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, $h_n = (1/2)\Sigma\, \partial\vartheta_m/\partial x \exp(-a|n-m|)$, 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 ($|x_A - x_{A'}| < l_o$, $l_o = \lambda_J l_H$)[3]. Thus, if the density of the A-vortices is low (i.e., $0 < H_e - H^*_{c1} \ll H^*_{c1}$), 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,

$$B(H_e) \simeq B_J + B_A, \quad B_A = (2L_A/L_z)\exp(-a/2)(H_e - H^*_{c1})\tilde{\vartheta}(H_e - H^*_{c1}), \qquad (7)$$

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 $L \lesssim 1$ 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 $H_r - H^*_{c1} \cong \exp(-a/2)(a/2 + \ln l_o)^{-1}$ (here, a is assumed to be large: a>>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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