Fluctuations in the Josephson-Pancake combined vortex lattice

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Abstract

We study vortex fluctuations in strongly anisotropic layered superconductors placed in tilted magnetic fields where there are two alignments of vortices: pancake vortices (PV's) oriented along the c-axis, and Josephson vortices (JV's) along the ab-plane. For low enough out-of-plane magnetic fields H_c, the JV sublattice pins some PV's, confining several of their degrees of freedom. This can result in the suppression of PV thermal fluctuations and a weak increase in the out-of-plane vortex lattice melting field $B_z^{\rm melt}$ with increasing in-plane magnetic field H_{ab}.

Key words: Layered superconductor; tilted magnetic fields; vortex lattice melting; thermal fluctuations of the vortex chain-lattice.

Direct visualization [1–3] as well as magnetic [4,5] and transport [6,7] measurements show that oblique magnetic fields penetrate a strongly anisotropic layered superconductor as two perpendicular alignments of vortices. The PV lattice, oriented originally along the c-axis, is locally bent by currents generated by JV's, which are channelled in-between CuO_2 layers. Such an interaction between both vortex subsystems somewhat links the degrees of freedom of PV's and JV's, giving a quite unusual shape for the vortex lattice melting transition line on the $H_c - H_{ab}$ phase diagram [4–7]. The experimentally observed linear decay of the out-of-plane melting field $H_c^{\rm melt}$ with the in-plane magnetic field H_{ab} [4–7] was thermodynamically interpreted [8] via the linear increasing of the free energy of the crossing vortex lattice with H_{ab}. The fluctuation mechanism of this linear decay is probably related to the softening of the elastic constants of the PV sublattice by the c-axis component of the JV current. With further increasing the in-plane magnetic field H_{ab}, the out-of-plane melting field component shows a plateau-like dependence or even a slow increase [5,7,6]. The origin of this dependence was attributed to the trapping of some PV's by JVs [7,9]. In this paper we demonstrate how the sticking of PV's to JV's influences the PV thermal fluctuations and the vortex lattice melting transition.

Here we consider weak, $H_c < \Phi_0/(\gamma^2 s^2)$, out-of-plane magnetic fields H_c, when any z–x wall formed by JV's can effectively interact with only one PV row placed directly on the wall (see Fig. 1). In this case, the strongly pinned PV chains coexist with the very weakly deformed PV lattice settled between JV's [8]. However, the pinned PV rows (chains) restrict the degrees of freedom of the remaining PV's, fixing their y-displacement as $u_y(na_J) = 0$, with a_J equal to the distance between nearest JV walls, and n an integer. Thus, the "free" x-displacement u_x can be expanded via the usual Fourier integral as

$$u_x = \int\limits_{BZ} \frac{d^3\mathbf{k}}{(2\pi)^3}\, u_x(\mathbf{k})\, \exp(i\mathbf{k}r), \qquad (1)$$

where the integration in $\mathbf{k}$-space is done over the first Brillouin zone (BZ) assuming periodic boundary conditions: $k_x^2 + k_y^2 < 4\pi B_z/\Phi_0$ (B_z is the magnetic induction along the c-axis), $|k_z| < k_z^{\rm max} = \min(1/\xi_c, 1/s)$ with the c-axis coherence length ξ_c and distance between CuO_2 planes s. However, the y-displacement u_y

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of PV's confined between two neighboring PV chains (Fig. 1) can be expressed as

$$u_y = \int \frac{d\mathbf{k}_{xz}\, dq_y}{(2\pi)^2\, \pi}\; u_y(\mathbf{k}_{xz},\, q_y)\; \sin(q_y\, y)\; \exp(i\mathbf{k}_{xz}\mathbf{r}_{xz}), \quad (2)$$

with $\mathbf{k}_{xz} = k_x\mathbf{e}_x + k_z\mathbf{e}_z$, $\mathbf{r}_{xz} = x\mathbf{e}_x + z\mathbf{e}_z$, and unit vectors $\mathbf{e}_x$ and $\mathbf{e}_z$ along x and z axes. The wave vectors in the last Fourier expansion are restricted as $\sqrt{B_x/(\gamma\Phi_0)} \sim 1/a_J < q_y < 1/a_p$, $q_y^2 + k_x^2 < 4\pi B_z/\Phi_0$, and $|k_z| < k_z^{\max}$. Here, B_x is the in-plane magnetic induction. The y-component q_y of the PV wave vector is restricted from below because only waves with nodes on the neighboring JV walls can propagate in the PV lattice.

If, in addition, the c-axis magnetic field satisfies the inequality $H_c < \Phi_0/\lambda_{ab}^2$, the main contribution to the elastic free energy is related to the electromagnetic tilt rigidity of PV's:

$$\mathcal{F} = \frac{1}{2}\int \frac{d^3\mathbf{k}}{(2\pi)^3}\; \overline{U}_{44}\; u_x(\mathbf{k})\; u_x(-\mathbf{k})\; + $$
$$+\frac{1}{2}\int \frac{d\mathbf{k}_{xz}\, dq_y}{4\pi^3}\; \overline{U}_{44}\; u_y(\mathbf{k}_{xz}, q_y)\; u_y(-\mathbf{k}_{xz}, q_y) \quad (3)$$

where the elastic stiffness is the $\mathbf{k}$-independent constant $\overline{U}_{44} = \Phi_0 \ln(1+4\lambda_{ab}^2/c_L^2 a_p^2)/(32\pi^2\lambda_{ab}^4)$ as long as $|k_z| < k_z^* = \min(\pi/s, \gamma\sqrt{\ln(1+4\lambda_{ab}^2/c_L^2 a_0^2)}/\lambda_{ab})$. By using equation (3), the mean square displacements of PV's from their equilibrium positions associated with thermal fluctuations can be estimated as $\langle u^2\rangle = \frac{T}{\overline{U}_{44}}(\mathcal{N}_x + \mathcal{N}_y)$, where $\mathcal{N}_x$ and $\mathcal{N}_y$ are the number of the degrees of freedom attributed to PV displacements along the x and y axes: $\mathcal{N}_x = \int_{BZ} d^3\mathbf{k}/(2\pi^3) \approx k_z^* B_z/(\pi\Phi_0)$, while $\mathcal{N}_y = \int d^2\mathbf{k}_{xz} dq_y/(4\pi^3) \sim (k_z^*/\pi)\sqrt{B_z/\Phi_0}[\sqrt{B_z/\Phi_0} - \sqrt{B_x/(\gamma\Phi_0)}]$.

In order to understand qualitatively how the freezing of some degrees of freedom of PV lattice influences the vortex lattice melting transition, we can use the Lindemann criterion $\langle u^2\rangle = c_L^2 a_p^2 = \sqrt{\Phi_0/B_z}$ with the interpancake distance a_p and the Lindemann number c_L. The last equation can be approximately rewritten in the form

$$B_z^{\rm melt} - \frac{1}{2}\sqrt{B_z^{\rm melt} B_x/\gamma} = B_0 \quad (4)$$

with the melting field B_0 for $\mathbf{H}$ applied along the c-axis: $B_0 = c_L^2\Phi_0^3 \ln(1+4\lambda_{ab}^2/(c_L^2 a_p^2))/(64\pi T\lambda_{ab}^2 k_z^*)$. If an applied in-plane magnetic field satisfies the inequality $H_{ab} \ll 16\gamma B_0$, the dependence of $B_z^{\rm melt}$ on the in-plane field B_x is expressed as

$$B_z^{\rm melt} \approx B_0 + \frac{1}{2}\sqrt{\frac{B_x B_0}{\gamma}}. \quad (5)$$

The shift of the vortex lattice melting transition to higher out-of-plane magnetic fields by applying an in-plane field is related to the growth of the number of the mutual JV-PV pinning centers, resulting in the increase of the fraction of the frozen degrees of freedom of PV's. Nevertheless, an almost constant $B_z^{\rm melt}$ versus B_x is usually observed [5,7]. A possible reason for this discrepancy is that the transition line separating the lattice-chain state from the phase with the unpinned PV and JV sublattices does not depend of H_{ab} [9]. Thus, the growth of $B_z^{\rm melt}$ may be suppressed by defrosting the PV degrees of freedom, giving an an almost constant dependence $B_z^{\rm melt}(B_x)$.

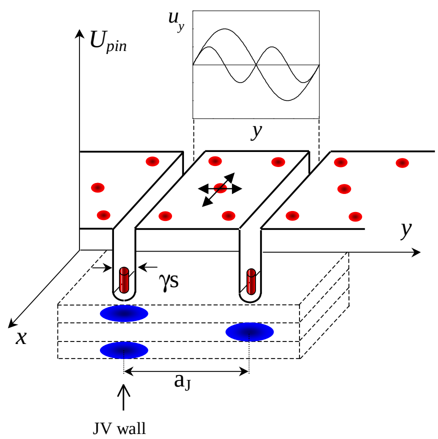

Fig. 1. Sketch of the mutual JV-PV sticking potential, trapping PV chains in the potential wells produced by the JV's. The very weakly deformed PV lattice confined between wells has less degrees of freedom: the y-displacement waves with nodes at the potential wells (examples plotted in the inset) can only propagate on the PV lattice.

In conclusion, the fluctuations of the pancake vortices in the mixed chain-lattice phase of the PV sublattice in the crossing vortex lattice structure are studied. We show that the linear decay of the out-of-plane vortex lattice melting field with increasing in-plane magnetic field is stopped due to the freezing of the PV degrees of freedom.

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