Phase Diagram and Dynamical Matching of Josephson Vortices in Mesoscopic Layered High-T$_c$ Superconductors

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Abstract

We study Josephson vortex lattice structures and their dynamics in micron scale layered High-Tc superconductors. Generally, superconducting vortices form the triangular lattice due to their repulsive interaction. However, the tendency drastically changes for Josephson vortices in micron scale sample due to strong influences from sample edge. Moreover, we find a unique dynamical effect due to dynamical matching with sample edge in flux flow states.

Key words: Josephson Vortex Lattice; Josephson Vortex Dynamics; Dynamical Matching

1. Introduction

Since the observation of intrinsic Josephson effects in layered High-Tc superconductors, Josephson vortex dynamics have attracted a great interest in connection with high-frequency device applications. Generally, most of experiments on intrinsic Josephson effects have been done on mesa types of micron scale samples for the purpose of clear detection of Josephson effects. Therefore, one may expect that sample edge is crucial for not only lattice structures of Josephson vortices but also their dynamics in such micron scale systems.

Recently, in Josephson vortex dynamics under tiny transport currents, interesting experimental results have been reported in micron scale sample of $Bi_2Sr_2CaCu_2O_8$(Bi-2212) by Ooi et al.,[1]. Their findings are summarized as follows. 1) An accurate regular periodic dependence of Josphson vortex flow resistance on the layer parallel magnetic field can be distinctly observed over a wide range of field (0.5 $\sim$ 4.0T). 2) The measured periodicity H_p is given by a relation $\frac{\phi_0}{2LD}$ where ϕ_0, L, and D are the flux quanta, the sample width perpendicular to the layer parallel field, and the layer periodicity along the c-axis, respectively.

In this paper, we report simulation results on H-T phase diagram of lattice structures of Josephson vortices in the micron scale sample. Furthermore, we clarify that dynamical matching effects of Josephson vortex lattice with sample edges gives rise to the regular field depedence of the Josephson flow resistance as observed by Ooi et al.,[1].

2. Numerical Simulations

The free energy of the system is given by Lawrence-Doniach model as $F_{LD} = \sum_\ell \int dr_{//}[mDn_s {v_\ell^{//}}^2 + J(1-cosP_{\ell+1,\ell}) + \frac{D}{8\pi}{B_{\ell+1,\ell}}^2]$, where n_s, D, and $v_\ell^{//}$, are the superfluid density, the layer periodicity, and the in-plane superfluid velocity in ℓ-th layer, respectively, and $P_{\ell+1,\ell}$ and $B_{\ell+1,\ell}$ are the phase difference and the parallel magnetic field between ℓ-th and $\ell+1$-th superconducting layers. From the free energy the time dependent equation for $P_{\ell+1,\ell}$ with Langevin noise $f_{\ell+1,\ell}$ are derived as $\gamma\frac{\partial P_{\ell+1,\ell}}{\partial t} = -\frac{\delta F_{LD}}{\delta P_{\ell+1,\ell}} + f_{\ell+1,\ell}$. In order to search equilibrium lattice structures of Josephson vortices at T, we solve the equation with gradual cooling from T_c to T.

Let us now show simulation results on H-T phase diagram of the lattice structure in micron scale samples.

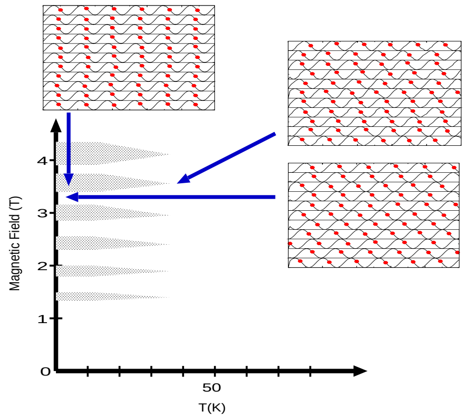

Fig. 1. The H-T phase diagram of lattice structure of Josephson vortices. The in-plane sample size is 2.5μ m. The square lattice structures are observed in the shaded regions.

Fig.1 is a typical result where the anisotropy ratio γ, the c-axis penetration depth λ_c, and the in-plane size perpendicular to magnetic field are taken as 500, 125 μ m, and 2.5 μ m, respectively. In the figure, the shaded regions indicate the appearance of the square like lattice although some lattice defects are observable. As shown in the figure, the square and the triangular lattice structures alternately appear with increasing magnetic field near the zero temperature. The square structure is also found to be unstable at high temperature region as seen in the inset. We check how the phase diagram changes with increasing the in-plane size L from 1.25 μ to 10.0 μ. Consequently, we find a fact that the periodicity in which the square structure emerges along the magnetic field axis decreases with increasing the in-plane sample size. In addition, we note that the square structure becomes not observable as L exceeds over about 10 μ m. In such a scale one may understand that finite size effects almost diminish.

Now, let us consider why the square structure appears only in the small scale sample. Generally, it is well-known that vortices favor the triangular lattice due to their repulsive interaction. On the other hand, the sample edge works as a square potential on the vortex lattice as long as the sample shape is square. This indicates that the sample edge can stabilize the square lattice structure. Thus, it is found that these interplay competes in small scale samples and the balance depends on the magnetic field. More details will be published elesewhere [2].

Next, let us show simulation results of dynamical behaviors of Josephson vortices under the c-axis parallel transport current in Fig.2. The Fig.2(a) displays the periodic dependence of the flow voltage on the magnetic field which are consistent with the experimental results [1], while the Fig.2(b) represents a size dependence of the flow resistance periodicity H_p in both real and numerical experiments [1,2].

Here, let us study an origin of the size-dependent accurate periodicity of the flow resistance. We find in the present dynamical simulations that the Josephson vortices strongly feel the sample edge potential by monitoring the vortex velocity, that is, the vortex speed strongly decreases near the edge [2]. Thus, if several vortices penetrate and exit at the same time, then the vortex flow speed(resistance) are found to be strongly suppressed. This result leads to a consequence that the periodicity is given by the relation $H_p = \frac{\phi_0}{2LD}$ in a case of the triangular lattice flow [2].

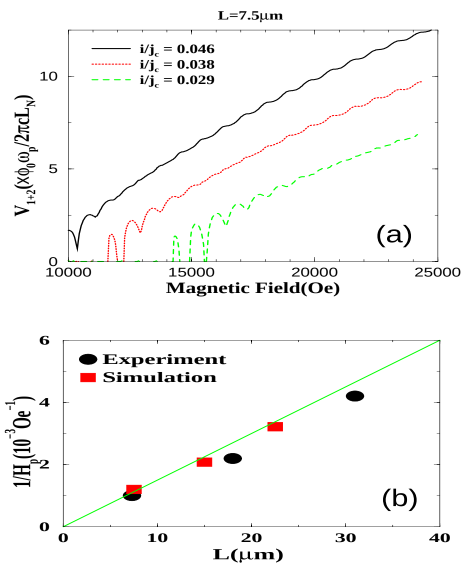

Fig. 2. (a) The current dependence of the flow voltage vs. the magnetic field in the sample size L=7.5μm. (b) A comparison between experimental and numerical results of the magnetic field periodicity H_p of the flow resistance. The line gives the relation $H_p = \frac{\phi_0}{2LD}$.

In summary, we studied that the structures of Josephson vortex lattice and their dynamics strongly dependent on the sample size. Consequently, we found that the presence of the sample edges enriches the statics and the dynanmics of Josephson vortices.

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References

[1] S.Ooi, K.Hirata, and T.Mochiku (Unpublished).

[2] M.Machida (Unpublished).