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Vortex dynamics and matching effect in superconductors with planar pinning arrays

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ABSTRACT

We have studied the dynamics of vortices interacting with periodic planar pinning arrays using molecular dynamics simulation. We consider three types of periodic pinning arrays consisting of long (L) and short (S) pinning intervals. Current–voltage curves and critical currents have been calculated as a function of vortex density for each pinning array model. Compared to the model with equally spaced pinning array, the models in which L/S is 2 show higher critical currents in certain vortex density range. This behavior comes from the appearance of broad matching peaks in the presence of planar pinning arrays. Meanwhile, in the models in which L/S is 1.618, the appearances of some of the matching peaks are suppressed because of the mismatch between the pinning interval and the vortex lattice constant. Thus, compared to the equally spaced model, the critical currents in this model are low in wide ranges of vortex density. On the basis of these results, we have discussed the matching effect in the presence of periodic arrays of planar pinning.

1. Introduction

The enhancement of the vortex pinning by introducing artificial pinning center is of great interest in the practical application of superconductor because it often causes the increase of the critical current (j_c). Therefore, over the past few decades, considerable efforts have been made to create artificial pinning sites that can immobilize vortices effectively. Since the pinning efficiency of periodic pinning arrays is higher than that of randomly distributed pinning, the fabrication of periodic pinning arrays has been one of attractive subjects. The pinning efficiency in periodic pinning arrays is substantially enhanced when the configuration of vortices is commensurate with that of pinning arrays. This phenomenon is called "matching effect", and this effect appears as peaks in the j_c vs vortex density (j_c–B) curve [1–3]. Recent progress of nanofabrication technique has provided well-controlled shape and arrangement of pinning sites, and a wide variety of periodic pinning arrangements has been studied extensively [4–13]. Furthermore, "quasi" periodic pinning array has also been investigated, and an unusual broad matching peak in j_c–B curve has been reported [14–18]. The "broadness" of these matching peaks is a strong advantage in practical applications requiring high j_c in a wide range of magnetic fields.

Recently, using deposition technique, superconducting/non-superconducting multilayer films whose non superconducting layer align at regular intervals have been fabricated (e.g. MgB_2/Ni layer [22,23], YBCO/Pr123 layer [24,25]) and the matching effect in the presence of periodic planar pinning arrays has attracted much attention. The vortex dynamics interacting with planar pinning arrays is analogous to the two-dimensional (2D) vortex dynamics in the presence of one-dimensional (1D) pinning arrays. The physics of 2D vortices in the presence of 1D periodic pinning potential has been studied both experimentally and theoretically [26–31]. In contrast to sharp matching peaks in the case of point pinning arrays, "broad" matching peaks appear in the case of 1D pinning arrays. The broad matching peaks have been also reported in MgB_2/Ni layer structure around the first matching field [23] where the pinning interval is equal to the height of the Abrikosov lattice. Previous theoretical studies have suggested that the broadness of these matching peaks comes from the flexible deformation of vortex lattice fitting in underlying pinning arrays [29,32].

In our previous paper, we investigated the vortex dynamics in the presence of the planar pinning array aligned at regular intervals using molecular dynamics simulation. We reported broad matching peaks in j_c–B curves and clarified various matching configurations in a wide range of vortex density [32]. However, we focused only on the planar pinning array aligned at regular intervals. As in the case of periodic arrays of point pinning, there are a number of possible periodic geometries of the planar pinning, and the difference in the geometry would affect the vortex dynamics and matching effect considerably. However, so far no studies have tried to investigate the vortex dynamics interacting with planar pinning arrays that are periodic but are aligned at "non regular intervals".

In this paper, to clarify the effect of planar pinning geometries on matching effect, we have investigated the vortex dynamics in

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the presence of three types of periodic pinning arrays consisting of long (L) and short (S) pinning intervals (e.g. $SLSLSL$c). Current–voltage curves and j_cs have been calculated as a function of vortex density for each pinning array model. Compared to the model with equally spaced pinning array, the models in which L/S is 2 show higher critical currents in certain vortex density ranges. Meanwhile, in the models in which L/S is 1.618, the appearances of some of the matching peaks are suppressed, which result in lower j_cs in wide ranges of vortex density compared to the equally spaced model.

2. Model and method

In this work, we consider a two dimensional slice in the x–y plane of an infinite three dimensional sample. We use periodic boundary conditions in the x–y plane and treat the vortices as stiff rods that are perpendicular to z direction. For simplicity, we assume planar pinning centers are dominant pinning centers, and ignore all the other kinds of pinning centers. We assume pinning planes are perpendicular to the x axis. The applied current is oriented in the direction of the y axis so that the Lorentz force acts perpendicular to planar pinning centers. Vortex motion is determined by solving the following overdamped equation [19–21,32]

$$\eta \frac{\mathrm{d}}{\mathrm{dt}} \boldsymbol{r}_i = \boldsymbol{F}_{\mathrm{vv}} + \boldsymbol{F}_{\mathrm{pl}} + \boldsymbol{F}_{\mathrm{th}} + \boldsymbol{F}_{\mathrm{L}}. \tag{1}$$

Here, η is the viscous coefficient which is set to unity, $\boldsymbol{r}_i$ is the location of ith vortex, $\boldsymbol{F}_{\mathrm{vv}}$ is the repulsive force from other vortices, $\boldsymbol{F}_{\mathrm{pl}}$ is the pinning force, $\boldsymbol{F}_{\mathrm{th}}$ is the thermal noise, and $\boldsymbol{F}_{\mathrm{L}}$ is the Lorentz force.

The form of $\boldsymbol{F}_{\mathrm{vv}}$ can be derived from the London theory as [33],

$$\boldsymbol{F}_{\mathrm{vv}} = \sum_{j \neq i}^{N_{\mathrm{v}}} \frac{\Phi_0^2}{8\pi^2 \lambda^3} K_1\left(\frac{|\boldsymbol{r}_i - \boldsymbol{r}_j|}{\lambda}\right) \frac{\boldsymbol{r}_i - \boldsymbol{r}_j}{|\boldsymbol{r}_i - \boldsymbol{r}_j|}, \tag{2}$$

where λ is the penetration depth, Φ is the flux quantum, N_{v} is the number of vortices, and K_1 is the modified Bessel function. The planar pinning center is modeled as an attractive channel with a width of $2R_{\mathrm{pl}}$, and F_{pl} is given by

$$\boldsymbol{F}_{\mathrm{pl}} = -f_{\mathrm{pl}} \sum_{k=1}^{N_{\mathrm{pl}}} x_{ik}(1 - x_{ik}^2)\Theta(1 - |x_{ik}|)\hat{x}. \tag{3}$$

Here, f_{pl} is the pinning strength parameter of planar pinning, N_{pl} is the number of the planar pinning sites, $x_{ik} = (\hat{x} \cdot \boldsymbol{r}_i - P_k)/R_{\mathrm{pl}}$ with P_k the x-coordinate of kth planar pinning, and Θ is the Heaviside step function. The elementary pinning force of planar pinning f_{max} is estimated as 0.38 f_{pl} from Eq. (3). The thermal fluctuation is assumed to be a Gaussian white noise. The Lorentz force F_{L} is assumed to act on all vortices uniformly. Throughout this work, we take the magnetic penetration length λ as a constant parameter, and all lengths are measured in unit of λ, forces in unit of $f_0 = \Phi_0^2/8\pi^2\lambda^3$, energies in unit of $U_0 = \Phi_0^2/8\pi^2\lambda^2$, vortex density in unit of $B_0 = \Phi_0/\lambda^2$, and time in unit of $t_0 = \eta\lambda/f_0$.

We obtain the initial vortex position using simulated annealing method. After getting a static configuration, we start to apply Lorentz force and calculate the average vortex velocity in the x direction $\hat{v}_x$ using Eq. (1) at 0 K. Note that the third term of Eq. (1) is zero in all calculations after getting the static configuration. Then we increase the applied Lorentz force linearly with time, and calculate $\hat{v}_x$ for each increment. The average vortex velocity and the Lorentz force are related to macroscopically measured voltage and current respectively. We define the critical depinning force f_{cr} as the force when $\hat{v}_x$ reaches the value of 0.03 times of linear response in an unpinned ideal sample ($\hat{v}_x = f_{\mathrm{L}}$). This criterion was used in previous reports and thought to be valid [3,32,34]. The f_{cr} represents the transition point between pinned and moving states of a vortex, and is related to the critical current density.

We consider three types of periodic pinning array composed of two pinning intervals long L and short S. In model A, a unit cell consists of one S and one L, and the ratio of L to S is 2. In model B, a unit cell consists of two S's and one L, and the L to S ratio is 2. Hereafter, we denote these two configurations as (SL) and (SSL), respectively. Model C has the same configuration as model A, i.e. (SL), but the L to S ratio is 1.618 (1.618 is approximation value of golden ratio). In Fig. 1a and b, we show the schematic figures of models A, B and C. We set S and L so that the average pinning interval equals to 1.2λ (e. g. $S = 0.8\lambda$, $L = 1.6\lambda$ in model A). The model whose planar pinnings align at 1.2λ intervals has been studied in our previous paper [32], and we denote this model as model D.

3. Results

3.1. f_{cr}–B curve in model A

In Fig. 2, we show the examples of average vortex velocity $\hat{v}_x$ versus the Lorentz force curve at 1.39B_0 and 2.08B_0. The values of f_{cr} correspond to the positions of the jumps of $\hat{v}_x$ from zero in these curves. In Fig. 3a and b, we show f_{cr} and free vortex ratio (FVR) as a function of vortex density in model A. The dotted lines indicate the previous results in the model D. The value of FVR represents the ratio of depinned vortices to all vortices below f_{cr}. We found that step-like changes of f_{cr} and FVR corresponds to drastic change of vortex configurations. In Fig. 4a–c, we show vortex positions (black circles) and planar pinning arrangements (shaded regions) at 0.14B_0, 1.22B_0 and 5.00B_0. Up to ~0.2B_0, vortices form an ordered lattice along to the planar pinnings as shown in Fig. 4a. In this range, the interval between the "lines" of vortices along the y axis, "d_v", is equal to $S + L$, and all vortices are pinned. Thus FVR equals to zero, and f_{cr} equals to f_{max}. In the range from 0.7B_0 to 1.9B_0, vortices again form an ordered lattice whose d_v equals S as shown in Fig. 4b. In these configurations, three lines of vortices along the y-axis appear in a unit cell, and one of them is depinned. Thus, FVR equals to 1/3, so that f_{cr}'s are simply estimated as (1 − 1/3) f_{max}. Similarly, in the range from 4.2B_0 to 6.7B_0, vortices form an ordered lattice whose d_v equals S/2 as shown in Fig. 4c. Here, FVR equals to 2/3, so that f_{cr} equals to 1/3 f_{max}. Meanwhile, in the vortex density range other than those described above, vortices do not form an ordered lattice fitting in the periodic array of planar pinnings (see Fig. 5a for $B = 2.50B_0$), or vortices form oblique lattices whose bases are parallel to x axis (see Fig. 5b for $B = 0.28B_0$). In both cases f_{cr} becomes lower than that simply estimated from FVR. It should be noted that the oblique lattices "geometrically" fit in the periodic pinning array. However, in these lattices the vor-

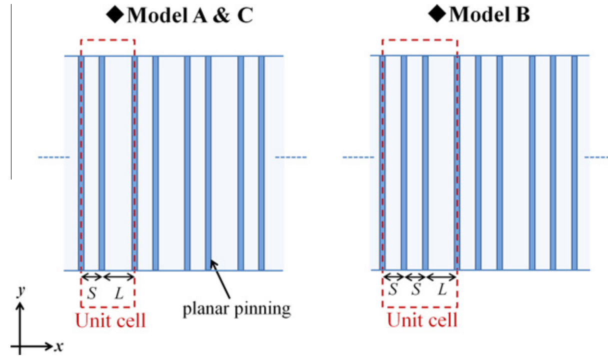

Fig. 1. Schematics of the planar pinning configurations composed of two pinning intervals long (L) and short (S), (a) models A and C, (b) model B. Dark region denote planar pinning centers while bright ones are regions without pinning centers.