Plastic vortex flow in current-driven disordered Josephson junction networks

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Abstract

Current-driven dynamics of vortices in Josephson junction networks under a magnetic field is studied numerically. In the presence of structural disorder in JJNs, it is found that there are two kinds of mechanisms of plastic or elastic depinning of vortices, and then the depinning critical current follows a scaling relation.

Key words: Josephson junction;array;plastic flow;vortices

Vortices in disordered Josephson junction networks (JJNs) driven by bias currents show various dynamical behaviors, which depend strongly on the strengths of driving current and disorder. In this study we investigate the critical current and current-driven dynamics of JJNs in a magnetic field, using a numerical simulation based on the resistively shunted junction (RSJ) model.

The JJN consider here consists of a 2-dimensional array of superconducting sites (islands) with an $N \times N$ square lattice structure, where each pair of the nearest-neighbor sites are connected by a Josephson junction in both the x- and y-direction, and positional disorder is introduced into of the island configuration. In the absence of the disorder, the lattice constants are the same in both directions. The bias currents are injected (taken out) in the y-direction at the top (bottom) row. In order to analyze the time evolution of superconducting phases of the JJN, we employ the RSJ model. The phase on the i-th site is denoted by ϕ_i. The equations of motion of ϕ_i are given by a set of N-coupled nonlinear differential equations:

$$\sum_j^{\mathrm{N.N.}} g_{ij}[\dot{\phi}_i - \dot{\phi}_j] = I_i - \sum_j^{\mathrm{N.N.}} J_{ij} \sin(\phi_i - \phi_j - A_{ij}), \quad (1)$$

where J_{ij} is the critical current of the junction between the i and j sites, $\sum^{\mathrm{N.N.}}$ means summation on the nearest-neighbor sites, A_{ij} the line integral of the vector potential, $g_{ij} = 1/R_{ij}$ where R_{ij} is the junction resistance, the external bias current $I_i = I(-I)$ at the top (bottom) of the array and $I_i = 0$ otherwise, and we set $2e/\hbar = 1$. We calculate voltage drops across the array in the direction of the bias current, V, which is averaged temporally and spatially at the top (bottom) row of arrays, and also the sum of absolute values of vorticities due to vortices and antivortices excited in the array, N_e, which is averaged temporally. The effects of the external magnetic field and structural disorder of JJNs are taken into consideration in the vector potential with the Landau gauge [1,2]. According to Ref. [1], we introduce a random displacement field δ into the positions of sites, by which the position of the i-th site is given by $\mathbf{r}_i = (n^x + \delta_i^x, n^y + \delta_i^y)$, where the lattice constant of the array for $\delta_i^{x,y} = 0$ is set to be unity, $n_x(n_y)$ an integer, and $\delta_i^x(\delta_i^y)$ the deviation of the i-th site and given by a random number in $[-\Delta, \Delta]$. Numerical simulations of eq.(1) are performed using a algorism and method in [3]. The average number of quantum flux per plaquette in the array is chosen to be $f = 5+1/9$. The resistance parameter is set as $R_{ij} = 1$.

Figure 1 shows V and N_e plotted against the bias current I for a weak disorder case ((a): $\Delta = 0.02$) and

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a strong disorder case ((b): $\Delta = 0.15$). All the critical currents of junctions are chosen to be unity ($J_{ij} = 1$). The zero and finite voltage regimes correspond to

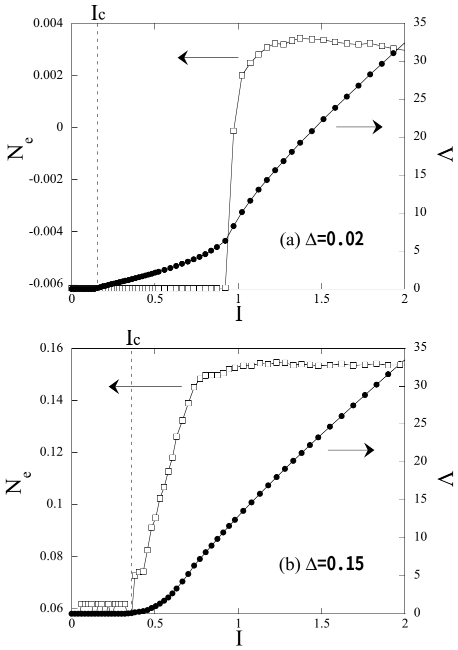

Fig. 1. $I - N_e$ and $I - V$ characteristics.

pinned and moving states of vortices, respectively. The critical current between them is denoted by I_c, which corresponds to the depinning current of vortices. From the comparison between figures 1(a) and (b), it is found that there is an obvious difference in behaviors of the $I - N_e$ characteristics. For the weak disorder, N_e show a rapid increase above a certain current (≈ 0.95) greater than I_c. On the other hand, for the strong disorder, N_e increases just above I_c. From analyses of dynamics of vorticity [5], it is found that the increasing behaviors of N_e is caused by nucleation (excitation) of vortex-antivortex pairs.

These results in fig. 1 mean that the mechanisms of depinning of vortices are different between these weak and strong disorder cases. For the weak disorder (fig. 1(a)), the depinning of the vortex lattice is driven by elastic deformation, and plastic deformation does not occur dominantly. Therefore, most of the vortices in the vortex lattice start to move at I_c and then elastic vortex flow is formed. In this state vortex-antivortex pairs are not excited. In the large I ($\geq 0.95(> I_c)$) regime, however, excitations of vortex-antivortex pairs are caused by a dynamical effect of the strongly driven vortex lattice in the presence of disorder of arrays. Then the excited vortices and antivortices move in the array, together with the moving vortex lattice. On the other hand, for the strong disorder (fig. 1(b)), vortex-antivortex pairs are excited at I_c prior to the depinning of vortex lattices. When $I \geq I_c$, excited vortices are driven in the direction vertical to the flow of bias currents, forming complicated flow paths (channels) in the array. This is the plastic depinning of vortices and antivortices due to a nuleation effect.

Next we focus on the relationship between the strength of I_c and the pinning and flow mechanisms of vortices. If it is assumed here that J_{ij} has an anisotropy that J_x and J_y in the x- and y-directions respectively, as reported in [3], J_y/J_x works as a control parameter that determines the strength of pinning. In fig. 2, we plot I_c against the change in J_y/J_x for both the weak and strong disorder cases. The following relations are

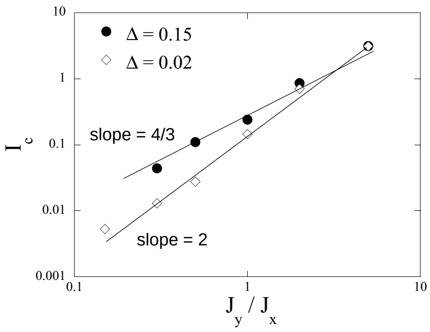

Fig. 2. I_c-J_y/J_x characteristics.

observed here: $I_c \propto (J_y/J_x)^{\frac{4}{3}}$ and $\propto (J_y/J_x)^2$ for the weak ($\Delta = 0.02$) and strong ($\Delta = 0.15$) disorder cases, respectively. Based on the scaling theory of pinning of elastic manifolds in a random potential [4], these behaviors of I_c are understood from a scaling relation $I_c \propto (J_y/J_x)^{\frac{4}{4-D}}$, where D is an effective dimension of correlation between vortices. The difference in the slopes in fig. 2 reflects the difference in D, i.e., the elastic flow for weak disorder has a 2-dimensional elastic correlation: $D = 2$, and the plastic flow for the strong disorder has a 1-dimensional nature due to its channel-like structures of flow: $D = 1$.

The computation in this work was done using the facilities of the Supercomputer Center, Institute for Solid State Physics, University of Tokyo.

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