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Motion of current-driven vortex solids with weak pinning in the Corbino disk

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Abstract

We report on the dynamic response of a weakly disordered vortex lattice driven by a radial current I in an amorphous Mo_xGe_{1-x} film with a Corbino-disk (CD) geometry. In CD, the vortices circulate around the center of the sample by feeling a nonuniform Lorentz force inversely proportional to the radius of rotation. We observe the peak in the dynamic critical current, as well as, in the static critical current, as a function of the magnetic field. This means that, even when the vortices are in circular motion, they feel the maximum pinning force just prior to 'dynamic' melting. As I is increased in the solid state, the vortices near the center are first depinned and then exhibit the plastic-flow-like rotation. This is in contrast to previous work for a $YBa_2Cu_3O_{7-\delta}$ single-crystal, in which the elastic rotation is observed.

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1. Introduction

How the vortices respond dynamically to an applied current is an important issue from the practical and fundamental points of view. This is because the vortex motion limits the various applications of superconductivity and this study will reveal new insights into the friction or plastic motion of solids [1,2].

The vortex dynamics confined within the Corbino disk (CD) is of particular interest, since the vortices circulate around the center of the sample by feeling a frustrated Lorentz force inversely proportional to the radius (r) of rotation [1–4]. In this work, we perform the transport measurements for a (weakly disordered) vortex lattice driven by a radial current I in an amorphous a-Mo_xGe_{1-x} film with a CD contact geometry, focusing on how the driving force (I) and elasticity (magnetic field B) change the vortex dynamics.

We observe the peak ($B_{p,dyn}$) in the dynamic critical current $I_{c,dyn}$, as well as that (B_p) in the static critical (depinning) current I_c, as a function of B (i.e., so-called the peak effect (PE) [5,6]), in accord with recent work for the strip-shaped a-Mo_xGe_{1-x} films [7]. The result indicates that, even when the vortices are in circular motion, they feel a maximum pinning force just prior to 'dynamic' melting.

Here we study the spatial (r) dependence of the vortex motion, more precisely, transverse velocity correlations of the circulating vortices, in different fields including the PE regime by measuring the current–voltage (I–V) characteristics at the two voltage probes placed radially [1,8,9]. As I is increased in fields corresponding to the solid state, when at equilibrium, the vortices near the center are first depinned, exhibiting the plastic-flow-like rotation. This result is similar to that which has been observed for the a-Mo_xSi_{1-x} films with stronger pinning [9], but opposed

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to previous work for a single-crystal of $YBa_2Cu_3O_{7-\delta}$ [1], in which the rigid elastic rotation is observed. With further increasing I, the plastic-flow [10] gradually changes to the liquid-like rotation, where the vortex dynamics is dominated by the local Lorenz force. The preliminary data related to present work have been reported elsewhere [8,9].

2. Experimental

The 330 nm thick a-Mo_xGe_{1-x} film was prepared by rf sputtering on a Si substrate held at room temperature [7,11]. The mean-field transition temperature defined by a 95% criterion [12,13], i.e., the linear resistivity decreases to 95% of the normal-state resistivity, is 6.3 K and the zero-resistivity temperature is 6.2 K. At 4.1 K, where all the data presented in this paper were taken, the upper-critical field B_{c2} defined by a 95% criterion [12] is 4.8 T and zero-resistivity field B_c is 3.8 T. The arrangement of the electrical contacts is shown in the inset of Fig. 1. The current flows between the contact, +C, of the center and that, −C, of the perimeter of the disk [14,15]. The inner radius of CD is 2.3 mm. The distances from the center of the sample to (the center of) the contacts P_1, P_2, and P_3 (indicated with 1, 2, and 3 in the inset) are 0.85, 1.45, and 1.90 mm, respectively, which serve as the two voltage probes (V_{12} and V_{23}) with different radiuses, r_{12} and r_{23} ($r_{12} < r_{23}$). The films were directly immersed in liquid ^{4}He to ensure good thermal contact. The field B was applied perpendicular to the plane of the film.

3. Results and discussion

Fig. 1 shows the critical current I_c (full circles) measured at the inner voltage probes (r_{12}) at 4.1 K plotted against B, where I_c is defined as a threshold current at which the vortices start to move. The values of I_c are extracted from the I–V curves, such as shown in Fig. 2a and b, using a 10^{-7} V criterion. We also plot the 'dynamic' critical current $I_{c,dyn}$,

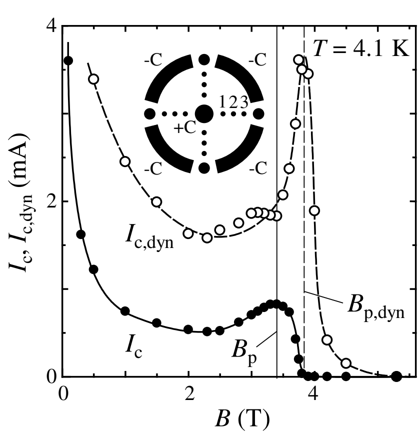

Fig. 1. B dependencies of the critical current I_c (full circles) and dynamic critical current $I_{c,dyn}$ (open circles) measured at the inner voltage probes at 4.1 K. Vertical lines represent the location of the peak fields, B_p (left) and $B_{p,dyn}$ (right). Other lines are guides for the eye. Inset: Arrangement of the electrical contacts.

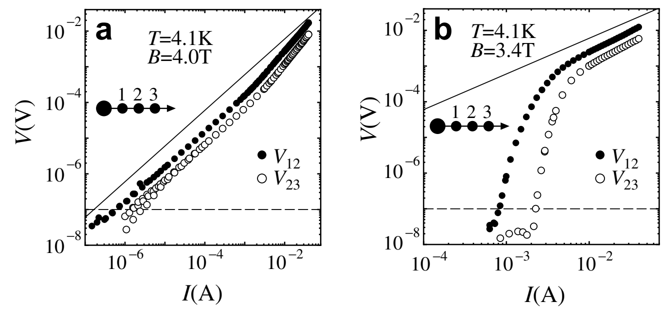

Fig. 2. (a) I dependencies of V_{12} (full circles) and V_{23} (open circles) at 4.1 K in 4.0 T (in the liquid phase) and (b) in 3.4 T (in the solid phase). The straight lines represent the I–V characteristics in the normal state. Horizontal dashed lines mark 10^{-7} V. Inset: Schematic illustration of the voltage contacts.

which is determined by linear extrapolation of the flux-flow (linear) part of I–V curves to the zero voltage. $I_{c,dyn}$ reflects the pinning strength for driven vortices in the flux–flow state [7]. The peak field $B_{p,dyn}$(=3.8 T) of $I_{c,dyn}$ is higher than that B_p(≈3.4 T) of $I_c(B)$ and very close to a field of ≈3.8 T(=B_c) where I_c vanishes, consistent with recent work for the strip-shaped films [7]. The result indicates that, even when the vortices are in circular motion, they feel a maximum pinning force just prior to 'dynamic' melting.

Fig. 2a and b depict the I dependencies of V_{12} (full circles) and V_{23} (open circles) at 4.1 K in 4.0 T (in the liquid phase) and in 3.4 T (≈B_p in the solid phase), respectively, plotted on a log–log scale. The straight line in each figure represents the I–V characteristics in the normal state. In the liquid phase the linear relation persists up to the high currents, while in the solid phase I–V curves exhibit strong nonlinearity even at low I. We observe qualitatively the same I–V curves as shown in Fig. 2b over the broad fields (B = 0.1–3.4 T) studied in the solid phase. It is commonly observed for different B that, as the applied current I exceeds certain critical values, a detectable voltage ($V = 10^{-7}$ V) appears first at r_{12}. This means that in the solid phase, as well as in the liquid phase, the vortices in the inner portion (at r_{12}) are first depinned and those in the outer portion (at r_{23}) are depinned at higher I.

In Fig. 3a and b we display the electric fields $E(r)$ (voltages divided by the distance between the voltage contacts) measured at the two voltage probes in B = 4.0 and 3.4 T, respectively. The plotted data were extracted from the I–V curves shown in Fig. 2a and b. In the liquid phase (4.0 T), the slope of log$E$ vs log$r$ is nearly −1 (indicated with a dashed line) for all I studied, as is expected for the liquid-like rotation. It is noted that in the solid phase (3.4 T) the ratio of E_{12} to E_{23} is extremely large at low I (near $I_c(r_{23}) \approx 2.2$ mA), where E_{12} and E_{23} are the electric fields measured at r_{12} and r_{23}, respectively. This result reflects the fact that the velocities of the vortices rotating in the outer portion of the sample are smaller and they feel the pinning potential more effectively [8,9].

These features are more clearly seen by plotting the values of E_{12}/E_{23} for fixed B against I, as shown in Fig. 4. For