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Critical dynamics associated with dynamic disordering near the depinning transition in different vortex phases

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ABSTRACT

We study a depinning transition based on transient dynamics of vortices driven by a suddenly applied dc current, focusing on whether a difference in the equilibrium vortex phase that can lead to a different vortex flow will change the critical behavior. After preparing an ordered initial vortex configuration, we measure the time evolution of voltage associated with dynamic disordering in three magnetic fields, corresponding to the ordered phase (OP), disordered phase (DP), and coexistence phase. The critical behavior of the depinning transition is commonly observed in these phases, pointing to the universality of the transition. However, the critical behavior is most marked in the coexistence phase, while the suppression of the critical region and that of dynamic disordering are observed in OP and DP, respectively, whose origin is attributed to the different flow states among these phases.

1. Introduction

The dynamics of driven elastic media interacting with quenched disorder is determined by the competition between elasticity of the lattice and disorder of the substrate, that is, the pinning potential. When the strength of pinning exceeds elasticity, the lattice deforms plastically. The plastic motion of solids is widely observed in nature [1] and therefore has attracted a great deal of attention. In theoretical models of plastic depinning, when a dc driving force F is suddenly applied to the many particle system, the particles move in the form of complex fluctuating channels, where some particles are mobile while others remain pinned [2–25]. In the case of the ordered initial configuration, that is, the ordered lattice containing a small number of defects, the driven particles are gradually pinned to the random pinning centers until the final ($t \to \infty$) steady state is reached. This process is called dynamic disordering. When F is lower than a critical depinning force F_c, all the particles are finally pinned, whereas, when $F > F_c$, nearly a constant number of particles are flowing in the $t \to \infty$ steady state. The theory predicts that the transient behavior associated with dynamic disordering exhibits a nonequilibrium phase transition, which is called a plastic depinning transition [2]. In experiments such a transient behavior was originally observed in a vortex system of $NbSe_2$ single crystals [4].

Recently, we have provided evidence of the plastic depinning transition [2] using a vortex system confined in a Corbino disk (CD) [26–31] of an amorphous (a-) Mo_xGe_{1-x} film [18,19]. In the presence of the radial current, vortices rotate around the center of the sample by feeling a frustrated Lorenz force inversely proportional to the radius r of rotation. After preparing an ordered initial vortex configuration, we applied a dc current I with a sharp rise and measured the time-dependent voltage $V(t)$, where I and V correspond to the dc driving force F and the mean vortex velocity v, respectively. We observed a decay of $V(t)$ toward a steady state $V(t \to \infty)$ ($\equiv V^{\infty}$), indicative of dynamic disordering. The relaxation time $\tau(I)$ to reach the steady state diverges around the depinning current I_d determined from I–V characteristics with a critical exponent close to the predicted one [18,19]. Quite recently, critical dynamics associated with plastic depinning has been also reported in a "jamming" regime of NbS_2 single crystals [32].

In the meantime, we performed further measurements for the *disordered* initial vortex configuration and found that $V(t)$ in response to the dc drive exhibits a gradual *increase* toward V^{∞}, indicative of dynamic *ordering* [33]. The relaxation time to reach the steady state diverges at the same I_d for the ordered initial configuration. Our results clearly showed that while the transient response depends on the initial vortex configurations, the transient time as well as the final mean vortex velocity only depends on the applied current, and the critical behaviors of the depinning transition are identical. They were the demonstration of the fact predicted by numerical simulations and other more indirect experiments [20].

In our previous work mentioned above, the applied magnetic field B was fixed at each temperature T. It is well known that the strength of B can control the stiffness of the vortex lattice and that this may cause a significant change in the vortex dynamics [12]. In fact, we revealed earlier from flow noise measurements for

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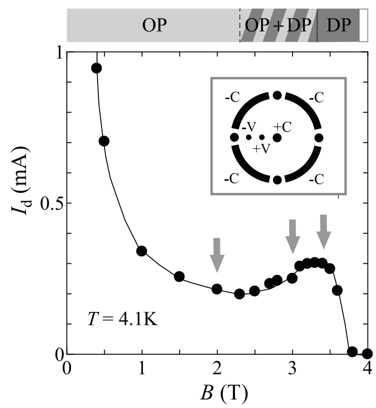

Fig. 1. I_d at 4.1 K plotted against B. Arrows indicate the fields of 2.0, 3.0, and 3.4 T, where $V(t)$ is measured. A solid line is a guide for the eye. Top: The equilibrium vortex phase diagram as a function of B, where OP, OP + DP, and DP represent the ordered phase, coexistence phase, and disordered phase, respectively. Inset: Arrangement of electrical contacts of CD.

CD of a-Mo_xGe_{1-x} films that with increasing B at constant T, the vortex state undergoes a structural transition from an ordered (or weakly disordered) lattice phase (OP) to a disordered amorphous-like phase (DP) at around the peak field B_p of $I_d(B)$ [34]. Just prior to B_p, there exists a coexistence phase of OP and DP [26,27], where flow noise exhibits a sharp rise and pinning is most effective. The equilibrium phase diagram as a function of B is schematically shown in the top of Fig. 1.

Although we have obtained evidence of the depinning transition [18,33], it remains unclear whether a difference in the equilibrium vortex phase that can lead to a different vortex flow will change the critical behavior of the depinning transition. To clarify this issue, in this work we perform systematic comparative measurements of $V(t)$ associated with dynamic disordering in different B, corresponding to the OP, coexistence phase, and DP. The critical behavior of the depinning transition is commonly observed for these phases, pointing to the universality of the transition. However, the critical behavior is most marked in the coexistence phase, while the suppression of the critical region and that of dynamic disordering are observed in OP and DP, respectively, whose origin is attributed to the different flow states among these phases.

2. Experimental

The a-Mo_xGe_{1-x} film with thickness of 330 nm was prepared by rf sputtering on a Si substrate held at room temperature [34]. The mean-field transition and zero-resistivity temperature in zero field are $T_c = 6.3$ and 6.2 K, respectively. Arrangement of electrical contacts [26,30] is shown schematically 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, which produces a radial current density that decays as $1/r$. The inner radius of CD is 0.8 mm. Voltage contacts, +V and −V, were used to measure the voltage V generated by vortex motion. Using a mode-locking resonance where the ac current was superimposed with the dc current I, we previously found rotating vortex-lattice rings composed of triangular vortex arrays in the CD sample [30]. In the present work, we measured the time-dependent voltage $V(t)$ just after the dc I with a sharp rise ($\lesssim$15 ns) was suddenly applied to the vortex system. $V(t)$ enhanced with a preamplifier was acquired and analyzed using a fast-Fourier transform spectrum analyzer with the time-resolution of up to 40 kHz. Typical shape of the current rise $I(t)$ is illustrated in the main panel of Fig. 1(a) of [33]. The sample was directly immersed into the liquid ^{4}He and all the data were measured at 4.1 K. The magnetic field B was directed perpendicular to the plane of the film. We employed a zero-field-cooled (ZFC) mode; i.e., the sample was cooled from the normal state to the superconducting state in zero field with no applied current.

3. Results and discussion

Figs. 2(a), 2(b), and 2(c) display the selected data of the I–V characteristics measured in 2.0, 3.0, and 3.4 T, respectively, plotted on a linear–linear scale. In the inset of each figure, the same data is plotted on a log–log scale. A depinning current I_d is defined as a threshold current (indicated with an arrow) at which the vortices start to move [8]. The B dependence of I_d is shown in Fig. 1. The peak of I_d indicative of the peak effect [35–39] is observed at a field of $B_p = 3.3$ T before I_d vanishes at a “melting” field (= 3.8 T). The upper-critical field is around 4.9 T and there is a vortex liquid phase between 3.8 and 4.9 T. Below, we present the data of the transient vortex dynamics, $V(t)$, measured in 2.0, 3.0, and 3.4 T (indicated with arrows in Fig. 1), which correspond to the OP prior to the peak-effect regime, coexistence phase, and DP, respectively.

Since this work focuses on the dynamic-disordering process, it is needed to prepare the ordered initial vortex configuration where a very small number of dislocations (topological defects) are present. For this purpose, we specifically employed the ZFC mode to induce vortices, thereby avoiding a highly pinned metastable disordered state, which would be expected in the field-cooled (FC) mode. Furthermore, to completely heal the disorder that may remain in the vortex lattice, we shook the vortices by applying sinusoidal ac drive [20,40]. We determined the amplitude and frequency of the ac drive as follows:

(i) First, we applied the ac currents with certain amplitudes and frequencies f for several minutes, which yield the ac voltages with amplitudes $|V_{ac}|$ ranging from 10 to 1000 μV and f ranging from 0.1 to 100 kHz in the $t \to \infty$ steady state.

(ii) Then, we froze the vortex configuration by shutting off the ac current. In contrast to the case of the charge-density-wave system [41,42], the vortex configuration of driven vortex matter stays unchanged when the driving force is turned off [4,43]. After waiting for a few minutes at zero current, we applied the dc current of $I = 1$ mA with a sharp rise at $t = 0$ and measured $V(t)$.

(iii) To quantify the degree of order for the initial ($t = 0$) vortex configuration in comparison with that for the final ($t \to \infty$) configuration, we extract the values of V^0/V^∞ [i.e., $V(t \to +0)$ divided by $V(t \to \infty)$] from the data of $V(t)$, such as shown in Figs. 3(a)–3(c). While the initial vortex configuration is of course always more ordered than the final configuration, the larger values of V^0/V^∞ imply that the degree of order for the initial configuration is higher.

The results for $B = 3.0$ and 3.4 T are displayed as color maps in Figs. 4(a) and 4(b), respectively. Here, the horizontal and vertical axes represent $\log|V_{ac}|$ and $\log f$, respectively, and open circles indicate the points at which the data were taken. With increasing V^0/V^∞, the color changes from blue ($V^0/V^\infty = 1.0$) to red ($V^0/V^\infty = 1.6$), as indicated in the right-hand side of the maps. It is evident that the values of V^0/V^∞ for 3.4 T are generally smaller than those for 3.0 T, implying that the dynamic-disordering process in DP (3.4 T) is less marked compared to that in the coexistence phase (3.0 T). We find for either field that with increasing $|V_{ac}|$ and f, V^0/V^∞ shows a trend to increase and takes nearly constant values at $|V_{ac}| > 200$ μV and $f > 10$ kHz. Based on these results, we determine the amplitude and frequency of the ac drive, yielding $|V_{ac}| = 500$ μV and $f = 50$ kHz, that is used in preparing the ordered initial vortex configuration. We consider that the method presented here can be conveniently and widely used to heal the vortex lattice [16,20] and to check if the most ordered lattice at equilibrium ($I = 0$) is indeed prepared for given T and B.