Plastic depinning in superconducting vortices

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Abstract. We study a plastic depinning phenomenon in a sheared vortex system in a Corbino-disk superconductor, where some vortices are mobile while others remain pinned. We measure the time-dependent voltage $V(t)$ just after the dc drive due to the dc current $I$ with a sharp rise is suddenly applied to the vortex system. We find decaying $V(t)$ toward the steady-state value, indicating that the moving vortices are gradually pinned. The decay time $\tau(I)$ diverges at around a depinning current, as determined from the static $I-V$ characteristics. The value of $\tau$ is dependent on the initial vortex configuration, while the critical dynamics is insensitive to it. These results provide a strong support for the plastic depinning transition.

1. Introduction
In type-II superconductors quantized flux lines induced by a magnetic field $B$ repel each other and they are driven by a Lorentz force due to an applied current $I$. Thus, the vortex system can be used extensively as a general model system to study various nonequilibrium many-body effects [1]. Recently, we have found a novel dynamic transition, indicative of a reversible to irreversible flow transition (RIT), in a periodically sheared vortex system in a Corbino-disk (CD) superconductor [2, 3]. This transition was originally observed in a colloidal particle system, where the irreversible collisions that give rise to chaotic dynamics can also cause a system to self-organize to avoid future collisions [4, 5]. When a displacement of particles per cycle is small, they return to their initial position at the end of each cycle of a periodic shear. This is identified with reversible flow. As the displacement exceeds a critical distance for RIT, the particles do not return to their initial position. This is considered as irreversible flow. This RIT has also been interpreted in terms of an absorbing transition [9-11]. Within the interpretation, the irreversible regime corresponds to the fluctuating active state where particles are diffusing, while the reversible regime corresponds to the absorbing state where the particles are self-organized and absorbed into a nonfluctuating quiescent state [7]. We have obtained evidence for RIT with the critical behavior similar to that of the absorbing transition in our vortex system [3]. The result suggests the universality of these dynamic transitions.

In the meantime, it has been shown by simulation that the plastic depinning transition would occur in many-particle systems with random pinning and that it exhibits a critical dynamics similar to that of the absorbing transition [12]. When a dc force $f$ is suddenly applied to the particles, they move in the form of complex fluctuating channels, where some particles are mobile while others remain pinned. The moving particles are gradually pinned to the pinning centers. When $f$ is lower than the depinning threshold $f_d$, all the particles are finally pinned and thus this is identified with an absorbing state. By contrast, for $f > f_d$, nearly a constant number
of particles are flowing in a steady state and hence this is considered to be an active state. The depinning phenomenon is widely observed in nature, but the true nature of the depinning transition is still not fully understood. We have measured the time-dependent voltage $V(t)$ to detect the dynamic response of vortices to the suddenly applied dc current $I$ larger than the depinning threshold $I_d$ and observed decaying $V(t)$. This result implies that the moving vortices are pinned gradually and finally $V(t)$ approaches a steady-state voltage, where nearly a constant number of vortices are flowing. The decay time $\tau(I)$ is found to diverge at the depinning current $I_d$, as determined from static $I-V$ characteristics, suggesting that plastic depinning is a dynamic phase transition. In this work, to get insight into the plastic depinning phenomenon, we conduct detailed measurements of $V(t)$ in the same vortex system. Specifically, we have changed the initial vortex configurations, that is, the number of depinned vortices at $t = 0$ by changing the field-sweep process prior to measurements. It is expected that the difference in the initial vortex configurations would alter the transient vortex dynamics $V(t)$ and the relaxation time $\tau(I)$. To demonstrate the depinning transition, however, it is necessary to verify that the critical behavior is insensitive to the initial vortex configurations.

2. Experimental

The 330-nm-thick $a$-Mo$_2$Ge$_{1-x}$ film was prepared by rf sputtering on a Si substrate held at room temperature [13]. Mean-field transition and zero-resistivity temperatures are 6.3 and 6.2 K, respectively. The vortex motion can be studied from the voltage $V$, which is proportional to the average velocity, as a function of the dc drive due to the dc current $I$. Arrangement of silver electrical contacts is shown schematically in the right inset of Fig. 1(a). 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 $1/r$, where $r$ is a radius of rotating vortices. The inner radius of CD is 0.8 mm. We used the voltage contacts, +V and -V, to measure the voltage $V$. The time-dependent voltage $V(t)$ enhanced with a preamplifier was taken and analyzed using a fast-Fourier transform spectrum analyzer with the time-resolution of up to 40 kHz.

3. Results and discussion

All the data presented in this paper were taken at 4.1 K in 3.0 T, which corresponds to the coexistence vortex phase composed of ordered vortex lattice and amorphouslike disordered phase, where pinning is very effective [13, 14]. The main panel and left inset of Fig. 1(a) show the $I-V$ characteristics plotted on linear-linear and log-log scales, respectively. The depinning current $I_d$, at which the vortices start to move, is determined from the onset of voltage. Precisely speaking, it is difficult to determine the exact value of $I_d$, because it is dependent on the experimental resolutions of $V$. In this work, we have measured $V$ with improved resolution ($> 10^{-8}$ V) than before ($> 10^{-7}$ V), which causes a slight decrease in $I_d$ from 0.35 to 0.25 mA, as indicated with an arrow in the main panel and a dashed line in the inset.

Now, we focus on the transient vortex dynamics, that is, $V(t)$, in 3.0 T just after the dc current $I$ with a sharp rise is applied to the vortex system. In our previous experiment [3] we firstly decreased the field from 3.0 to 2.6 T and then increased up to 3.0 T before applying dc current $I(t)$ with a rise time as small as $10^{-8}$ s at $t = 0$. This initial field-sweep process was necessary to avoid a situation that a large number of vortices are strongly pinned in the initial state, which is most likely realized in field-cooled mode. In fact, when the field of 3.0 T was applied in the normal state and then the film was cooled through $T_c$ with no applied current, decaying $V(t)$ is not clearly visible. In this work, in order to examine a change in transient vortex dynamics that might occur when the initial vortex configuration is changed, we have decreased the field down to zero, instead of 2.6 T, each time before starting the measurements of $V(t)$ in 3.0 T. It is expected that this initial field-sweep process extending to even lower field
The data points fall onto a curve expressed as $V(\alpha) = 1\º(\beta)$. Plotted on a log-log scale in the inset, giving circles in Fig. 1(b), here, we use the following relaxation function, which was employed previously [3, 7, 12]:

$$V(t) = V^\infty - (V^\infty - V(0)) \exp\left(-t/\tau\right)/t^{\nu}.$$  

Here, we use $\alpha \approx 0.5$ near $I_d$, consistent with the previous simulation [12]. As shown with solid circles in Fig. 1(b), $\tau(I)$ diverges at $I_c = 0.20 \pm 0.10$ mA that is close to $I_d \approx 0.25$ mA and the data points fall onto a curve expressed as $\tau \propto (I - I_c)^{-\nu}$ with $\nu \approx 1.33$. The same data are plotted on a log-log scale in the inset, giving $\nu = 1.33 \pm 0.20$. This is close to the value $(\nu = 1.26 \pm 0.15)$ obtained in our previous experiment [3]. Open circles show $\tau(I)$ in the previous

![Image](image-url)

**Figure 1.** (a) $I-V$ characteristics at 4.1 K in 3.0 T plotted on a linear-linear scale. An arrow indicates the location of the depinning current $I_d$. Inset: (Left) The same data on a log-log scale. A dashed line marks $I_d$. (Right) Arrangement of the electrical contacts of CD. (b) $\tau$ vs $I$ (solid circles) obtained in the present experiment, where the field was decreased to zero before measuring $V(t)$ in 3.0 T, and that (open circles) obtained from previous work [3], where the field was decreased to 2.6 T before measuring $V(t)$ in 3.0 T. The present data diverge at $I_c = 0.20 \pm 0.10$ mA, as indicated with a vertical dashed line, and previous ones diverge at $I_c = 0.37 \pm 0.15$ mA, both of which are close to $I_d \approx 0.25$ mA. Solid and dashed curves indicate a power-law fit. Inset: The same data and their fit plotted on a log-log scale. The symbols and lines correspond to those in the main panel.
Figure 2. (Color online) Transient $V(t)/V^\infty$ at 4.1 K in 3.0 T just after the dc current $I$ with amplitudes of 0.8, 1.0, 1.2, 2.0, 3.0, and 4.0 mA (from top to bottom) was applied at $t = 0$.

experiment, where more vortices were pinned at $t = 0$ [3]. One can see a trend that $\tau$ obtained in this work is slightly larger than that in our previous work. This is reasonable considering the fact that, as more vortices are depinned at $t = 0$, more time $\tau$ is needed to relax into the steady state. It is important to note that critical dynamics, $\tau(I)$, near $I_c$, as well as the critical points, $I_c = 0.20 \pm 0.10$ and $0.37 \pm 0.15$ mA for present and previous work, respectively, is nearly independent of the initial vortex states, providing a strong support for the dynamic transition.

The exponent $\nu \approx 1.3$ obtained in this work is close to $\nu = 1.36 \pm 0.06$ reported in the simulation for the depinning transition in two dimensions (2D) [12] and $\nu_{RIT} = 1.3 \pm 0.3$ for RIT found previously in the periodically sheared vortex system in the same CD superconductor [3]. It is also close to $\nu_{RIT} = 1.1 \pm 0.3$ and $1.33 \pm 0.02$ found in the colloidal experiment in 3D and simulation for random organization in 2D [7], respectively. All these results strongly suggest that the nonequilibrium RIT, absorbing, and depinning transitions actually occur in our 2D vortex system and exhibit the similar critical behavior.

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