Critical behavior associated with transient dynamics near the depinning transition

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Abstract. We study the general phenomenon of plastic depinning using a vortex system confined in a Corbino-disc superconductor. For an ordered initial vortex configuration, the vortices driven by a suddenly applied dc current (force) are gradually pinned to random pinning centers, indicating dynamic disordering. This is detected from the decaying of voltage $V(t)$ (mean velocity) toward a steady-state value $V^\infty$. On the other hand, when the initial configuration is disordered, a gradual increase of $V(t)$ toward $V^\infty$ is observed, reflecting dynamic ordering. In both cases, relaxation times to reach the steady state exhibit a power-law divergence at the depinning current. Our results clearly show that the transient response depends on the initial vortex configurations: however, 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. To the best of our knowledge, this work is the first to demonstrate this fact predicted by numerical simulations and other more indirect experiments (e.g. Pérez Daroca et al 2011 Phys. Rev. B 84 012508).

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1. Introduction

When a dc driving force $F$ is applied to the many-particle system interacting with random pinning centers, the particles move in the form of complex fluctuating channels, where some particles are mobile while others remain pinned [1]. This phenomenon, called plastic depinning, has received considerable attention and has been studied extensively [1–24] in various physical systems, including colloids, electron crystals, charge-density waves (CDW), magnetic domain walls and vortices in type-II superconductors. Practically, understanding the pinning and depinning processes of driven systems is of great importance, e.g., for the application of logic and memory devices in spintronic [25] and flux-based superconducting circuits. From a fundamental viewpoint, the depinning phenomenon has also attracted growing interest. It is described in terms of a continuous phase transition: $v \sim (F - F_c)^\beta$, where $v$, $F_c$ and $\beta$ are the velocity, the critical driving force at which the system goes from a pinned state to a moving one [1, 11, 16] and a positive constant, respectively.

In the meantime, dynamic computer simulations modeling a colloidal system [26–28] have proposed an interesting possibility that plastic depinning can be characterized as a dynamic transition from a nonfluctuating (pinned) to a fluctuating (moving) state, which may fall into the same universality class as the absorbing transition [1, 14, 29]. In this picture, the moving particles driven by a suddenly applied dc force $F$ are gradually pinned to the random pinning centers and the mean velocity decays with time $t$. This process, which we call dynamic disordering, was found originally in a vortex system of NbSe$_2$ single crystals [5]. When $F$ is lower than $F_c$, all the particles are finally pinned. Thus, this is identified with an absorbing state. On the other hand, when $F > F_c$, nearly a constant number of particles are flowing in the steady state. Hence, this is considered to be an active state [1].

Recently, we actually verified [19, 20] this prediction [1] in a vortex system confined in a Corbino disc (CD) [30–35] of an amorphous ($a$-)Mo$_x$Ge$_{1-x}$ film, where complicated edge effects are absent. After preparing an initial vortex configuration composed of the ordered lattice with nearly no dislocations at $t = 0$, we applied a dc current $I$ with a sharp rise and measured the time-dependent voltage $V(t)$. Here, $I$ and $V$ correspond to $F$ and the mean vortex velocity $v$, respectively. We observed a decay of $V(t)$ toward a steady state, indicative of dynamic disordering, with a relaxation time $\tau_{dd}(I)$ that diverges around the depinning current $I_d$ determined from $I$–$V$ characteristics [19, 20]. The results provide evidence for the plastic depinning transition with a critical behavior similar to that of the absorbing transition [1, 14, 36, 37]. Quite recently, the critical dynamics associated with plastic depinning has been also reported in a ‘jamming’ regime of NbS$_2$ single crystals [38].

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A previous simulation [1] and experiment on the CD [19] focused on the dynamic disordering process. On the other hand, when the initial vortex configuration is highly disordered (as is often the case with actual systems), one may expect quite a different transient vortex dynamics in response to the dc drive: instead of dynamic disordering, the dynamic ordering process would be predominantly observed before the steady state is reached [21, 39]. Then, an interesting question arises as to whether such dynamically ordered vortices would also exhibit the critical behavior of the depinning transition or to what extent the critical behavior is visible for different initial vortex configurations, independent of the degree of disorder. To the best of our knowledge, this question has not been studied theoretically or experimentally, although some useful information has been presented in recent simulations and experiments [1, 21]. Here, we conduct a comparative experiment exploring the dynamic ordering as well as the dynamic disordering phenomenon by using the same vortex system as employed in [19] but by preparing different initial vortex configurations. We find that for the disordered initial configuration, \( V(t) \) in response to the dc drive \( I \) with a sharp rise exhibits a gradual increase toward the steady-state value, reflecting the dynamic ordering process. The relaxation time \( \tau_{do}(I) \) required for the system to reach the steady state diverges at around \( I_d \), similarly to what has been observed in the dynamic disordering process.

2. Experiment

The \( a\)-Mo\(_{x}\)Ge\(_{1-x} \) film with a thickness of 330 nm was prepared by radio-frequency sputtering on a Si substrate held at room temperature [40]. The superconducting transition temperature in zero field \( (B = 0) \) is 6.2 K. The arrangement of electrical contacts is schematically shown in the right inset of figure 1(a). The current flows between the contact +C of the center and −C of the perimeter of the disc, which produces a radial current density that decays as \( 1/r \), where \( r \) is the radius of rotating vortices. The inner radius of the CD is 0.8 mm. Voltage contacts, +V and −V, were used to measure the voltage \( V \) generated by vortex motion. We measured the time-dependent voltage \( V(t) \) just after a dc current \( I \) with a sharp rise \( (\lesssim 15 \text{ ns}) \) was suddenly applied to the vortex system. The \( V(t) \) enhanced with a preamplifier was taken and analyzed using a fast-Fourier transform spectrum analyzer with a time-resolution of up to 40 kHz.

The typical shape of the current rise \( I(t) \) is illustrated in the main panel of figure 1(a). Here, the ordinate is normalized by the magnitude of the current \( I \) at the steady state. The left inset displays an enlarged view of \( I(t) \) near \( t = 0 \) and \( I \) (the steady-state value), where a tiny damped oscillation arising from the current source is visible at \( t \lesssim 0.2 \text{ ms} \). This time is much shorter than the characteristic time \( (\gtrsim 1 \text{ ms}) \) for the vortex dynamics studied in this work. Moreover, the amplitude of the damped oscillation is less than 2% of \( I \). Therefore, this oscillation does not seriously affect the discussion in this paper.

The sample was directly immersed in liquid \( ^4\text{He} \). A magnetic field \( B \) was applied perpendicular to the plane of the film.

3. Results and discussion

In our previous work, we made measurements at 4.1 K in a field of 3.0 T corresponding to a peak-effect regime [30, 31, 41–45] where pinning-dominated plastic flow is most effective. In this work, we have lowered the temperature down to 2.0 K, which is slightly below the lambda point, to minimize possible temperature fluctuations in the sample that may lead to undesirable
Figure 1. (a) Typical shape of the current rise $I(t)$, where the ordinate is normalized by the magnitude of $I$. A region marked with a dashed rectangle is enlarged and shown in the left inset. The right inset illustrates an arrangement of electrical contacts of the CD. (b) $V(t)$’s at 2.0 K in 5.0 T in response to $I(t)$ with the magnitude of $I = 0.95$ mA for the ordered (black upper graph) and disordered (red lower graph) initial vortex configurations, which were prepared by shaking the vortices generated in the ZFC mode with ac current and prepared merely in the FC process without applying current, respectively. Black dotted and red solid lines are fits for the upper and lower graphs to equation (1), respectively.

Voltage fluctuations as well as to examine possible effects of temperature (thermal fluctuations) on the critical behavior. Furthermore, to observe both the dynamic disordering and dynamic ordering phenomena, we applied a field of 5.0 T giving rise to the ordered (or weakly disordered) vortex lattice where moderate plastic flow is expected just above\(^2\) the depinning current $I_d$ [40].

\(^2\) Here, we use a term ‘just above’ or ‘close to’ $I_d$ to indicate the current range ($I = 0.3$–$1$ mA) where the upward curvature of $V(I)$ is clearly visible.
Figure 2. (a) $I$–$V$ characteristics at 2.0 K in 5.0 T plotted on a linear–linear scale. In the measurements, first the field was increased from 0 to 5.0 T at 2.0 K without applying a current. Then, after waiting for more than 2 min, we started the $I$–$V$ measurements. For each data point ($I$), the waiting time to measure $V$ was 5 s. Inset: the same data plotted on a log–log scale. Arrows mark the location of the depinning current $I_d = 0.30$ mA. Other lines are a guide to the eye. (b) $I$ dependences of $\tau_{dd}$ (black open circles) and $\tau_{do}$ (red solid circles) exhibiting a divergence at $I_c \approx 0.30$ mA ($= I_d$). Black dotted and red solid lines represent the power-law fits of $\tau_{dd}(I)$ and $\tau_{do}(I)$, respectively. A vertical line indicates the location of $I_c$. Inset: the same data and their fits on a log–log scale. The symbols and lines correspond to those in the main panel. The slopes of the dotted and solid lines give the critical exponents, $\nu_{dd} = 1.4 \pm 0.4$ and $\nu_{do} = 1.4 \pm 0.3$, respectively.
current change. The depinning current $I_d$ is defined as a threshold current at which the vortices start to move, using a $10^{-8}$ V criterion [9]. The location of $I_d = 0.30$ mA is marked with vertical arrow(s). Upward (positive) curvature of $V(I)$ just above $I_d$ is clearly visible in the main panel, indicating that the vortex flow immediately after the depinning is plastic flow [46].

Figure 1(b) displays the transient voltage $V(t)$ at 2.0 K in 5.0 T just after the dc current $I = 0.95$ mA slightly above $I_d$ (see footnote 2) was suddenly applied to the vortex system at $t = 0$. Here, we have prepared the two opposite initial vortex configurations by employing the following two methods: (i) the ordered initial configuration composed of the vortex lattice, which was prepared by shaking the vortices that were generated in the zero-field-cooled (ZFC) mode, using ac current. (ii) The disordered initial configuration composed of the highly disordered vortex lattice, which was prepared in the field-cooled (FC) process without applying current. Here, we have made use of the generally accepted fact that in the FC mode a large number of dislocations (topological defects) are introduced into the vortex lattice when the sample contains random pinning centers, while more ordered lattices are formed in the ZFC mode [47] and/or with the application of the ac drive [17]. It is also important to note that the vortex configuration of the driven vortex solid stays unchanged when the drive is shut off [5]. This is known as a memory effect in the vortex system. This behavior is in contrast to what has been observed in the CDW system where the CDW can relax to a metastable state after the drive field is turned off [2].

As is clearly seen in figure 1(b), for the ordered initial vortex configuration (upper black graph), $V(t)$ slowly decays to a steady-state value $V^\infty \approx 0.031$ mV at $t \to \infty$ after showing a steep rise up to $V^0 \approx 0.048$ mV at $t \to 0^+$. The considerably larger value of $V^0$ than $V^\infty$ results from the fact that at the initial state ($t = 0$) the ordered vortex lattice is easier to move because dislocations are nearly absent, thus the effective pinning force is weaker. Since the voltage is proportional to the mean velocity of moving vortices, the observed decay of $V(t)$ indicates the dynamic disordering process of driven vortices. This behavior is essentially the same as that observed at 4.1 K in the same vortex system [19] and was originally found in NbSe$_2$ single crystals [5]. It has been suggested quite recently that information on dynamic disordering [21] and on the depinning transition [39] may be involved in individual voltage pulses in response to the ac drive with a rectangular pulse shape as well as in $V(t)$ in response to the dc drive.

In the case of the disordered initial vortex configuration (lower red graph), by contrast, $V(t)$ exhibits a gradual increase from $V^0 \approx 0$ to the steady-state value $V^\infty \approx 0.031$ mV. This behavior is interpreted as follows: in this case, the highly disordered vortex lattice feels the stronger effective pinning force at the initial state ($t = 0$) because a large number of dislocations are present. When the dc force with magnitude ($I = 0.95$ mA) just above (see footnote 2) the depinning threshold ($I_d = 0.30$ mA) is applied at $t = 0$, the pinned vortices would hinder the flow of the following vortices, resulting in small $V(t)$ just after $t = 0$. However, once some of the pinned vortices are depinned and take part in the vortex flow, they would help depin the rest of the pinned vortices. This process, which we call dynamic ordering, proceeds until the steady flow state is reached. Since the driving force ($I = 0.95$ mA) is set close to (see footnote 2) the depinning threshold ($I_d = 0.3$ mA), a considerable time $\approx 10$ ms is required for the vortex system to reach the steady state.

We have made the same comparative measurements of $V(t)$ using the two opposite initial vortex configurations at various current levels spanning the range $I = 0.6-3$ mA larger than
$I_d = 0.30 \, \text{mA}$. For currents smaller than $I_d$, $V(t)$ is not detected within our experimental resolutions. It is commonly observed, irrespective of the initial vortex configuration, that as $I$ increases, the relaxation times to reach the steady state decrease and the relaxation behaviors of $V(t)$ become much less pronounced around the largest value of $I \approx 3 \, \text{mA}$.

Such changes in the relaxation behaviors of $V(t)$ induced by increased $I$ are more clearly seen by plotting $V(t)/V^\infty$ (i.e. $V(t)$ divided by $V^\infty$) measured at different $I$ in the same figure, as shown in figure 3. Two sets of the $V(t)/V^\infty$ curves for the ordered and disordered initial vortex configurations are located above and below a line of $V(t)/V^\infty = 1$, respectively. One can see that pairs of the $V(t)/V^\infty$ curves for a given $I$, whose values are listed on the right-hand side of figure 3, are nearly symmetric with respect to the line of $V(t)/V^\infty = 1$ and seem to be of the same shape with respect to this line. It should be mentioned, however, that there is no physical reason why the shape of the two curves for a given $I$ should exactly coincide with each other, because the value of $V^0$ is determined not only by $I$ but also by a degree of disorder at $t = 0$; namely, the shape of the curves depends on a slight change in the initial vortex configuration. An important finding from figure 3 is that for a given $I$ the relaxation times characterizing the dynamic-disordering [$\tau_{dd}(I)$] and dynamic-ordering [$\tau_{do}(I)$] processes are close to each other. This will lead to an interesting question as to whether these characteristic times, $\tau_{dd}(I)$ and $\tau_{do}(I)$, exhibit the same critical behavior at around $I_d$.

To answer this question, we extract the values of $\tau_{dd}$ and $\tau_{do}$ from the relaxation curves of $V(t)$. Irrespective of the initial vortex configuration, we can reproduce the $V(t)$ curves measured well above $I_d$ using a simple exponential function, while in the vicinity of $I_d$ the functional form approaches a power law. Thus, to obtain the values of $\tau = \tau_{dd}$ and $\tau_{do}$, we fit $V(t)$ to the

**Figure 3.** Two sets of the $V(t)/V^\infty$ curves at 2.0 K in 5.0 T taken at different $I$ for the ordered and disordered initial vortex configurations, which are located above and below a line of $V(t)/V^\infty = 1$, respectively. The values of $I$ are shown on the right-hand side of the figure (from top to bottom and from bottom to top for $V(t)/V^\infty > 1$ and $V(t)/V^\infty < 1$, respectively).
following equation proposed in [1]:

\[ V(t) = (V^0 - V^\infty) \exp(-t/\tau)/\nu + V^\infty. \]  (1)

The results of the fits for \( I = 0.95 \text{ mA} \) are typically shown with black dotted and red solid lines in figure 1(b).

It follows from the analysis for different \( I \) that, for either initial vortex configuration, \( \alpha \) is \( \approx 0.4-0.5 \) in the vicinity of \( I_d \), which is close to \( \alpha = 0.5 \) predicted in the simulations \([1, 36]\), while \( \alpha \) becomes smaller at larger \( I \). As seen in figure 2(b), thus obtained \( \tau_{dd}(I) \) (black open circles) and \( \tau_{do}(I) \) (red solid circles) diverge at \( I_c = 0.30 \text{ mA} \), which is the same as \( I_d \) determined from the \( I-V \) characteristics within errors. The data points, \( \tau_{dd}(I) \) and \( \tau_{do}(I) \), fall onto single lines expressed as \( \tau_{dd} \propto (I-I_c)^{-\nu_{dd}} \) with \( \nu_{dd} = 1.4 \) (a black dotted line) and \( \tau_{do} \propto (I-I_c)^{-\nu_{do}} \) with \( \nu_{do} = 1.4 \) (a red solid line), respectively. The same data are shown on a log–log scale in the inset of figure 2(b), where the symbols and lines correspond to those in the main panel. The slopes of the dotted and solid lines directly give the critical exponents, \( \nu_{dd} = 1.4 \pm 0.4 \) and \( \nu_{do} = 1.4 \pm 0.3 \), respectively. At \( I \) larger than \( \approx 2 \text{ mA} \), the data points, \( \tau_{dd}(I-I_c) \) and \( \tau_{do}(I-I_c) \), deviate downward from the straight lines, suggesting that they are outside the critical region for the depinning transition and therefore excluded from the fits. Large error bars in the critical exponent arise from the ambiguity in the critical region, for which no theoretical prediction exists.

Let us first summarize the results on the dynamic disordering process. The \( \tau_{dd} \) versus \( I/I_c - 1 \) curve at 2.0 K obtained in this work (not shown here) is about a few times larger than that at 4.1 K obtained previously \([19]\). This would result from the enhanced relaxation due to the reduced temperature. However, the critical exponent \( \nu_{dd} = 1.4 \pm 0.4 \) obtained at 2.0 K is close to \( \nu_{dd} = 1.26 \pm 0.15 \) obtained at 4.1 K \([19]\) and to \( \nu_{dd} = 1.36 \pm 0.06 \) (\( \alpha_{dd} = 0.5 \)) reported in the simulation for the depinning transition for two dimensions (2D) \([1]\). The observed independence of the critical exponent from temperature or from the strength of thermal fluctuations supports the notion that the depinning transition as well as the absorbing transition is a nonthermal phase transition \([1, 14]\). The value of \( \nu_{dd} \approx 1.4 \pm 0.4 \) obtained in our vortex system is also close to the critical exponent 1.3 \( \pm 0.3 \) for the reversible–irreversible flow transition found in periodically sheared vortices in the same CD \([19]\) and to 1.33 \( \pm 0.02 \) reported in the simulation for random organization (absorbing transition) in 2D \([28]\). As pointed out earlier \([19]\), the above-mentioned proximity between the critical exponents for the depinning, reversible–irreversible flow and absorbing transitions strongly suggests the similarity between these dynamic transitions.

A main new finding in this work is that a critical behavior similar to that found in the dynamic disordering process is also seen in the dynamic ordering process. Within the error bars, the critical exponent \( \nu_{do} = 1.4 \pm 0.3 \) associated with dynamic ordering coincides with \( \nu_{dd} = 1.4 \pm 0.4 \) associated with dynamic disordering. The implication of the present results is that the characteristic time describing the critical dynamics for the depinning transition is not limited to \( \tau_{dd} \), as predicted theoretically \([1]\), but is more generalized to the ones including \( \tau_{do} \). In other words, the critical dynamics for the depinning transition can be observed in rather different initial vortex configurations, independent of the degree of disorder.

Quite recently, a seemingly similar critical dynamics of vortices was reported in NbS\(_2\) single crystals, where an unusual depinning current \( I_d^{0} \) was observed above the ordinary depinning current \( I_d \) \([38]\). The existence of the ‘second’ depinning current \( I_d^{0} \) was reported earlier in the \( N \)-shaped \( I-V \) characteristics for YNi\(_2\)B\(_2\)C single crystals \([48, 49]\). The authors of \([38]\) interpreted it in terms of the jammed vortex state. They found that \( V(t) \) in response to
the dc drive exhibits large-amplitude fluctuations and their lifetime diverges from both sides of $I_d^f$. The nature of jamming in vortex flow, as well as that of the second depinning current [48, 49], is nontrivial and not fully clarified. In our amorphous films a sign of jamming or the second depinning current has not been found so far, implying that the vortex states studied in NbS$_2$ single crystals [38] are much different from ours, probably much more complicated. Furthermore, the voltage fluctuations reported in NbS$_2$ crystals [38] do not directly represent the relaxation process for driven vortices, such as described by equation (1); the extracted lifetime for the voltage fluctuations is of the order of $10^3$ s, which is about five orders of magnitude larger than $\tau_{dd} \approx \tau_{do} \sim 10$ ms obtained in our work. Despite these facts, it is interesting that even for rather different vortex states and different nature of the (de-)pinning mechanisms, the transient vortex dynamics driven by the suddenly applied dc force exhibit a similar critical behavior. This may point to the universality of the plastic depinning transition. Also, it is of great interest to examine whether a similar critical behavior of the depinning transition is observed in other physical systems, such as the CDW system [2, 4].

4. Conclusions

Plastic depinning is widely observed in nature in driven many-particle systems interacting with random pinning centers. In this paper, we study the general phenomenon of plastic depinning based on the transient dynamics of vortices driven by a suddenly applied dc current $I$ in the CD at low $T$. For the ordered initial vortex configuration, $V(t)$ decays to either a zero or nonzero voltage depending on whether $I$ is smaller or larger than the depinning current $I_d$, respectively, which indicates dynamic disordering. For $I > I_d$, the decay time $\tau_{dd}(I)$ exhibits a power-law divergence at $I_d$, consistent with the simulation for the depinning and absorbing transitions [1, 14] and with the recent experiment performed at higher $T$ [19]. This result verifies the notion that these dynamic transitions are of nonthermal origin. On the other hand, for the disordered initial configuration, we find a gradual increase of $V(t)$ toward the steady-state value for $I > I_d$, which reflects dynamic ordering. The characteristic time $\tau_{do}(I)$ to reach the steady state exhibits a critical behavior similar to that of $\tau_{dd}(I)$ at around $I_d$. Our results clearly show that the transient response depends on the initial vortex configurations: however, 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 for both initial configurations are identical. To the best of our knowledge, this work is the first to demonstrate this fact predicted by numerical simulations and other more indirect experiments [21].

The implication of the present results is that they provide further convincing evidence for the plastic depinning transition and that the critical phenomenon associated with the depinning transition can be observed not only in the dynamic disordering process, as predicted theoretically [1], but also in wider processes involving the dynamic ordering process. In other words, it can be observed in rather different initial configurations, independent of the degree of disorder. This may suggest the universality of the plastic depinning transition.

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