Random organization of vortices under an anisotropic condition

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Abstract. Many colliding particles that are periodically sheared by ac drive self-organize to avoid future collisions, which is known as random organization. Recently, we have observed the random organization in the vortex system of a strip-shaped amorphous Mo_xGe_{1-x} film, where the vortices experience periodic local shear from ac drive and the random pinning potential. In this work, we study how random organization changes in the vortex system under the tilted field, where an anisotropic vortex-vortex interaction is introduced. We find that characteristic times of random organization for the vortices driven in the tilted direction are significantly smaller than those in the untilted field.

1. Introduction

A many particle system under an external driving force exhibits rich intriguing phenomena and has attracted much attention in recent years [1-7]. When particles are subjected to a periodic shear force, they collide with each other and gradually self-organize to avoid future collisions. This phenomenon is known as random organization [2-7]. In the final steady state, all the particles return to their initial position at the end of each cycle of a periodic shear, as long as the displacement amplitude of the ac shear is smaller than a threshold. This is called a reversible flow state. On the other hand, when the amplitude exceeds the threshold value, some particles do not return to their initial position, indicating that the collisions between the particles persist even in the steady state. This is called an irreversible flow state. A relaxation time of random organization, τ, that is, the time required for the system to settle into the steady state shows a power-law divergence at the threshold, indicating a dynamic transition from reversible to irreversible flow. The reversible-irreversible transition (RIT) is identified as the absorbing transition from non-fluctuating (reversible) to fluctuating (irreversible) states [8-14].

The RIT has been studied originally in periodically driven colloidal suspensions [1, 2] and then superconducting vortices in a Corbino disk where a global shear is applied [4, 5]. Recently, we have shown that random organization and RIT also occur in a strip-shaped superconducting film of amorphous Mo_xGe_{1-x} where a local shear due to random pinning is present [6, 7]. In the strip-shaped film, the spatial configuration of vortices and the vortex-vortex interaction are of course isotropic. However, when the magnetic field is tilted from normal to the sample plane, the vortex configuration and the resultant inter-vortex interaction become anisotropic. Recent studies have revealed that when the magnetic field is tilted at θ from normal to the sample plane,

hexagonal vortex lattice is expanded by a factor of $1/\cos\theta$ along the tilt direction [15-18]. More recently, we have found that the relation between the dynamic melting field and the velocity of the driven anisotropic lattice changes depending on the direction of the dc drive [18], indicating that not only the static vortices but also the moving vortices feel the anisotropic interaction. Therefore, it is reasonable to expect that random organization of the vortices mentioned above may also be influenced by the introduction of the anisotropy. This issue is of general interest, because the self-organization in an anisotropic condition is found in different physical systems, which include growth of atomic-scale patterns on an anisotropic substrate [19-21]. However, a detailed mechanism describing the transient process has not been clarified.

In this work, we study how random organization observed in the vortex system under the perpendicular (i.e., untilted) field changes in the tilted field, where an anisotropic vortex-vortex interaction as well as an anisotropic vortex configuration is introduced. We find that relaxation times of random organization for the vortices driven in the tilt direction are much smaller than those driven under the untilted field. The results indicate that the anisotropy introduced by the tilt field significantly limits possible configurations of vortices in the transient state and expedites the random organization process.

2. Experimental
A strip-shaped film of amorphous Mo_xGe_{1-x} with thickness of 350 nm was prepared by rf-sputtering on a Si substrate installed on a rotating stage kept at room temperature with water cooling. The transition temperature where the resistivity falls to zero is ~ 7 K at zero field. Since pinning potentials are shallow and randomly distributed in this amorphous sample, we can precisely detect detailed vortex motion using transport measurement. We measured the time evolutions of the ac voltage $V(t)$ responding to the square wave of ac current I_{ac} using a fast-Fourier transform spectrum analyzer. In each measurement, before applying I_{ac}, we prepared an initial vortex state with a random configuration by applying dc current yielding 100 μV, where the vortex-flow state is plastic flow [5]. Then, we applied I_{ac} yielding $V(t)$ whose amplitude in the steady state is $|V(t \to \infty)|(\equiv V^\infty) = 100$ μV. The displacement of a vortex per cycle is calculated from $d = \frac{v}{2f} = \frac{V^\infty}{Bl\cos\theta}\frac{1}{2f}$, where v is an average velocity of vortices, f a frequency of I_{ac}, l a distance between voltage terminals of the sample, and θ an angle of the field direction from normal to the sample plane. We changed d by varying f while keeping V^∞ constant. All measurements were performed at 4.1K, where the sample was immersed into liquid ^{4}He. The applied magnetic field was $B = 2.0$ T and $\theta = 0°$ and $36°$.

3. Results and discussion
First, we show the results for the field applied perpendicular to the sample plane ($\theta = 0°$). The representative data of $V(t)$ for $d = 6.0$ and 2.2 μm, corresponding to $f = 3500$ and 9500 Hz, are presented in figures 1(a) and (b), respectively. $V(t)$ in the long time duration reaching to the steady state is shown in the insets, where the high V region is enlarged and shown. We observe a transient behavior of $V(t)$ for all d studied. With increasing the cycle number, the amplitude of the voltage, $|V(t)|$, gradually increases and saturates to the steady-state value $V^\infty = 100$ μV. These results indicate random organization of the vortex system, where vortices become more mobile by repeating the periodic drive [4-6].

The amplitude of the voltage, $|V(t)|$, is fitted to the following relaxation function [2, 3],

$$|V(t)| = V^\infty - (V^\infty - V_0)\exp(-t/\tau)/t^\alpha, \tag{1}$$

where V_0 is $|V(t)|$ of the first pulse and α is a numerical parameter. In each figure, the result of the fit is indicated with a green line, from which we obtain the characteristic time of random organization to be $\tau = 60$ and 300 cycles for $d = 6.0$ and 2.2 μm, respectively. Here, the values

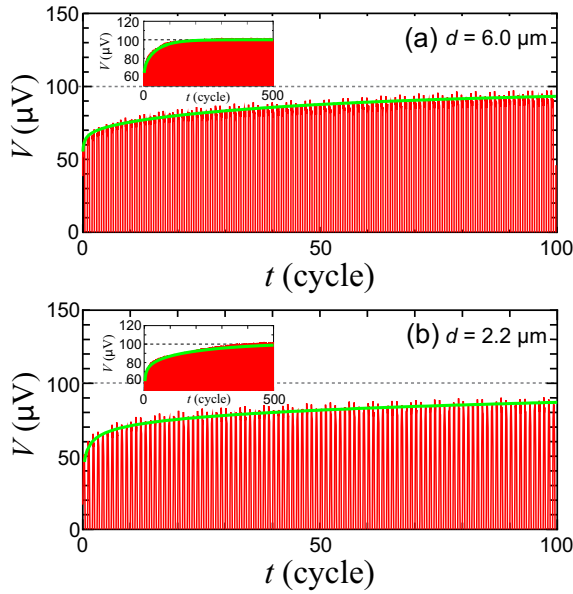**Figure 1.** The time evolution of the voltage $V(t)$ responding to the square wave I_{ac} yielding (a) $d = 6.0$ and (b) 2.2 μm measured at 4.1 K under the untilted ($\theta = 0$) field of 2 T. Green lines represent the fit of $|V(t)|$ to eq. (1). Horizontal dashed lines indicate the location of $V^\infty = 100$ μV. Insets: The high V region of $V(t)$ is enlarged and $V(t)$ in the long time duration is shown.
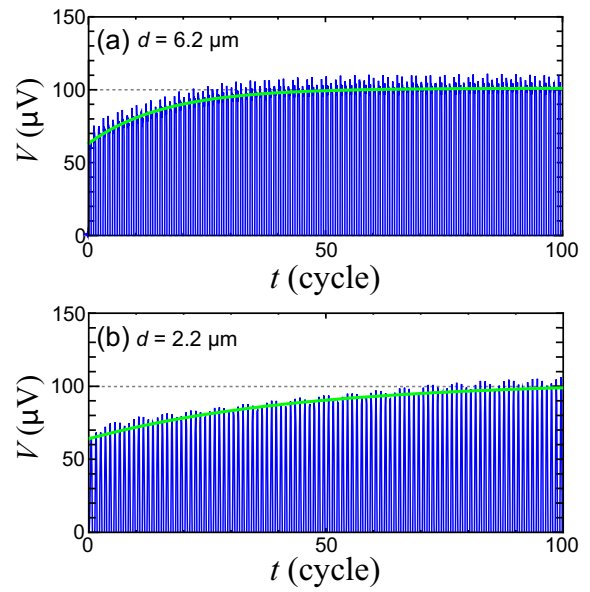
Figure 2. $V(t)$ responding to the square wave I_{ac} yielding (a) $d = 6.2$ and (b) 2.2 μm measured at 4.1 K under the tilted field ($\theta = 36°$) of 2 T. The direction of I_{ac} (/vortex motion) is perpendicular (/parallel) to the tilt direction. Green lines are the fit of $|V(t)|$ to eq. (1). Horizontal dashed lines indicate the location of $V^\infty = 100$ μV.

of α used in the fit are close to zero: $\alpha = 0.1$ and 0.18 for $d = 6.0$ and 2.2 μm, respectively. This fact is consistent with the theoretical prediction that the value of α only becomes relevant very close to the RIT. With decreasing d, τ seems to increase remarkably. The similar feature of $\tau(d)$ has been reported in our previous experiment carried out at 4.1 K in 4.0 T, where the critical divergence of τ has been observed with decreasing d in the irreversible phase [6].

Next, we show the results in the tilted ($\theta = 36°$) field. Here, the direction of the applied ac drive is parallel to the tilt direction, while the values of d as well as $V^\infty(= 100$ μV) are kept nearly same as the ones used in the untilted field. We again observe a transient behavior of $V(t)$, as shown in figures 2(a) and (b). However, the relaxation seems to be much faster. The values of τ derived from the fitting of $|V(t)|$ to eq. (1) are 15 and 38 cycles for $d = 6.2$ and 2.2 μm, respectively, which are significantly smaller than those obtained in the untilted field. We also use $\alpha \approx 0$ in the fitting for both cases. The fits are again satisfactory, as shown with green lines in figures 2(a) and (b). We have confirmed that under the perpendicular ($\theta = 0°$) field, $\tau(d)$ shows a trend to increase with decreasing the magnetic field. This result reflects the weakened random organization effect by the decreased vortex density. Thus, the marked suppression of τ by tilting the field observed here cannot be explained in terms of the decreased average vortex density (by 19 %).

We discuss the origin of the different values of τ under the untilted ($\theta = 0°$) field and tilted field. In the untilted field, the periodically sheared vortices show random organization from the randomly distributed initial configuration toward the less disordered steady-state configuration. In the transient process, the vortex-vortex (v-v) interaction is considered to be isotropic. On

the other hand, under the tilted ($\theta = 36°$) field, an ordered vortex configuration both for the undriven case and fast-driven steady-state case shows an expanded hexagonal lattice by a factor of $1/\cos\theta (\approx 1.24)$ along the tilt direction [15-18]. Thus, the v-v interaction along the perpendicular direction (p-direction) to the tilt direction is stronger than that along the tilt direction (t-direction). In the case of the transient situation from a disordered initial state to a less disordered final state, such an anisotropy is likely to dominate random organization. This is because for the disordered initial state in the tilted field, the average distance between the vortices along the p-direction is expected to be smaller than that along the t-direction and hence the v-v interaction along the p-direction is stronger than that along the t-direction. This means that during the transient process, possible vortex configurations along the p-direction are limited compared to those along the t-direction. This limited degree-of-freedom of the vortex motion, which is introduced by tilting the field, may be a possible origin for the decreased relaxation time τ in the tilted field.

Acknowledgements

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