Time evolution of the vortex configuration associated with dynamic ordering detected by dc drive

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Abstract. When a periodic shear force with a small amplitude $d_{inp}$ is applied to vortex assemblies having a random distribution, the vortices gradually self-organize to avoid future collisions and transform into an organized configuration. We showed recently that this random-organization or dynamic-ordering process can be detected from the time-evolution of voltage $V(t)$ that increases to a steady-state voltage. We also showed from the subsequent readout experiment of $V(t)$ using various ac amplitudes $d$ that the transient vortex configuration during random organization is not microscopically homogeneous but consists of the disordered and organized regions. In this work, we develop an alternative readout method using a dc drive. It is found that the dc method gives the same results as obtained from the ac one, which further supports our view of the coexistence regions. It is expected that both methods will be applied complementarily to detect the vortex configuration over a wide range of disorder.

1. Introduction

When an ac shearing force with a small shear amplitude $d_{inp}$ is applied to many particle assemblies having a random distribution, the particles gradually self-organize to avoid future collisions and change into an ordered configuration. This is called random organization or dynamic ordering by ac drive [1, 2, 3, 4]. In previous studies, we used a vortex system in amorphous Mo$_x$Ge$_{1-x}$ films to investigate these general phenomena. First, we performed measurements of the time evolution of the voltage $V(t)$, i.e., average velocity of vortices, associated with dynamic ordering by ac drive [5, 6, 7]. We call this experiment an input experiment. After freezing the vortex configuration at a desired time by turning off the ac driving current, we subjected the vortex assembly to ac drives with various amplitudes $d$ that give rise to dynamic ordering and/or disordering. We name this experiment a readout experiment. We found unexpectedly that the transient vortex configuration created during the ac dynamic ordering is not microscopically homogeneous but consists of disordered region (DR) and ordered region (OR) [7].

When the particles with an ordered initial configuration are driven in a random pinning potential by a small dc drive, they gradually transform into a disordered configuration. This is called dynamic disordering by dc drive [5, 8, 9, 10]. In contrast to the case of the ac dynamic ordering, the transient vortex configuration created during the dc dynamic disordering seemed to be homogeneous [11]. This leads to an interesting question: what is the origin of the coexistence regions? The results mentioned above [7] suggest that the use of the ac drive and/or the dynamic ordering process would be the necessary condition for the emergence of the coexistence regions.
It is of interest to clarify the origin of the coexistence regions. For this purpose, we must conduct additional experiments, such as the input experiment exhibiting the dynamic ordering by dc drive and the readout experiment detecting the vortex configuration during the dc dynamic-ordering process. Note, however, that in the dynamic-ordering experiment by dc drive, the initial and final vortex configurations are, in general, more disordered than those in the dynamic-ordering experiment by ac drive [5, 6, 12]. When the configuration in the input experiment is disordered, it is difficult to use the ac drive in the readout experiment. This is because the ac drive, which readily orders the disordered vortex configuration, cannot disorder the dynamic-ordering experiment by ac drive [5, 6, 12]. When the configuration in the input drive, the initial and final vortex configurations are, in general, more disordered than those in the dc dynamic-ordering process. Note, however, that in the dynamic-ordering experiment by dc drive, the initial and final vortex configurations are, in general, more disordered than those in the dynamic-ordering process.

2. Experimental
The $a$-Mo$_2$Ge$_{1-x}$ film with thickness of 330 nm was prepared by rf sputtering on a silicon substrate mounted on a water cooled rotating copper stage [5, 6, 10]. The superconducting transition temperature at zero field ($B = 0$) where the resistivity vanishes is $T_c$ =6.3 K. The width of the sample is 0.3 mm, along which the vortices are driven. The voltage contacts spaced at 1.2 mm were used to measure the voltage $V$ generated by vortex motion. The linear resistivity was measured using a standard four-terminal method. We also measured the time evolution of the voltage $V(t)$ just after the ac current $I_{ac}$ of square waveform or the dc current $I$ with a sharp rise was applied to the vortex system at $t = 0$. The voltage $V(t)$ enhanced with a preamplifier was recorded using a fast-Fourier transform spectrum analyzer with a time-resolution of up to 40 kHz. The amplitude of $I_{ac}$ was adjusted to yield an ac voltage with a desired amplitude $V^\infty(=|V(t \to \infty)|)$ at $t \to \infty$. The sample was directly immersed into the liquid $^4$He. The magnetic field $B$ was applied perpendicular to the plane of the film. All the data were acquired at 4.1 K in 3.5 T, corresponding to the peak-effect regime [13, 14, 15, 16, 17, 18, 19].

3. Results and discussion
We have known from previous studies that in our weak-pinning $a$-Mo$_2$Ge$_{1-x}$ films highly disordered vortex configuration is created in the field-cooled process, where many vortices are pinned to random pinning sites [6, 10]. Thus, in the input experiment, we prepared an initial vortex configuration by cooling the sample from 11 K ($> T_c$) to 4.1 K in a fixed magnetic field of 3.5 T. Then, we applied the square ac current $I_{ac}$ with a frequency of 12 kHz, yielding $d_{inp} = 1 \mu m$ and $V^\infty = 100 \mu V$, to the disordered initial vortex assembly at $t = 0$. The $t$-dependent voltage (divided by $V^\infty$), $V(t)/V^\infty$, generated by periodic motion of vortices is shown in figure 1, where $t$ is expressed as a number $n$ of cycles and the location of $V(t)/V^\infty = 1$ is indicated by the horizontal dashed line. The amplitude of the voltage, $|V(t)|$, shows a monotonic increase and relaxation to a steady-state voltage $V^\infty = 100 \mu V$ at many cycles ($n \geq 4000$). This indicates the dynamic ordering from the highly disordered vortex configuration to the relatively organized configuration characterized by $d_{inp} = 1 \mu m$ and $V^\infty = 100 \mu V$.

Figure 2(a) shows the “readout” voltage $V(t)/V^\infty$ for three different input vortex configurations, generated responding to the ac drive with a frequency of 4 kHz yielding $d = 3 \mu m$ and $V^\infty = 100 \mu V$. The red line represents $V(t)/V^\infty(= V_{n=0}(t)/V^\infty)$ for the input configuration prepared by the input ac drive with $d_{inp} = 1 \mu m$ and $V^\infty = 100 \mu V$ for $n = 0$ cycles, thus, corresponding to the most disordered initial configuration. The blue line indicates $V(t)/V^\infty(= V_{n=\infty}(t)/V^\infty)$ for the input configuration prepared by the ac drive yielding $d_{inp} = 1 \mu m$ for many ($n > 4000$) cycles, thus, corresponding to most organized initial configuration. The green line represents $V(t)/V^\infty(= V_{n=100}(t)/V^\infty)$ for the input configuration prepared by the ac
Figure 1. Input experiment of the dynamic ordering by ac drive: The time evolution of the voltage $V(t)/V^\infty$ for the highly disordered initial vortex configuration, generated in response to the ac drive with a frequency of 12 kHz yielding $d_{inp} = 1 \text{ µm}$ and $V^\infty = 100 \text{ µV}$. An arrow indicates $n = 100$ cycles. The horizontal dashed line marks the position of $V(t)/V^\infty = 1$.

Figure 2. (a) Readout experiment by ac drive: The readout voltage $V(t)/V^\infty$ for the input configuration created by the ac drive with $d_{inp} = 1 \text{ µm}$ and $V^\infty = 100 \text{ µV}$ after $n = 0$ (red line), many cycles ($n > 4000$) (blue line), and $n = 100$ cycles (green line), generated responding to the ac drive with a frequency of 4 kHz yielding $d = 3 \text{ µm}$ and $V^\infty = 100 \text{ µV}$. The purple line represents the fit of the data shown with the green line to Eq. (1) with $\alpha=0.60\pm0.04$. (b) Readout experiment by dc drive: The readout voltage $V(t)/V^\infty$ for the same input configuration as in (a); i.e., the configuration created by the ac drive with $d_{inp} = 1 \text{ µm}$ after $n = 0$ (red line), many cycles ($n > 4000$) (blue line), and $n = 100$ cycles (green line), generated responding to the dc drive yielding $V(t \rightarrow \infty) = 100 \text{ µV}$. The purple line is the fit of the data for the green line to Eq. (1) with $\alpha=0.57\pm0.01$. The horizontal dashed lines in (a) and (b) denote the location of 1.

The monotonic increase and decrease in $|V(t)|/V^\infty$ followed by a saturation to $|V(t \rightarrow \infty)|/V^\infty = 1$, indicative of dynamic ordering and disordering, respectively, are clearly observed as the red and blue lines. By contrast, a nonmonotonic fast decrease in $|V(t)|/V^\infty$ followed by a slow increase clearly seen as the green line indicates the emergence of the coexistence regions of OR and DR, as observed previously [7]. It is found that $V_{n=100}(t)/V^\infty$ is well reproduced by a weighted average of $V_{n=0}(t)/V^\infty$ and $V_{n \rightarrow \infty}(t)/V^\infty$ with a suitable weight parameter $\alpha$, which...
is expressed as:

\[ V_{n=100}^{fit}(t) = \alpha V_{n \to \infty}(t) + (1 - \alpha)V_{n=0}(t). \]  

(1)

The purple line shows the best fit of the data for the green line to Eq. (1), using \( \alpha = 0.60 \pm 0.04 \). It was shown in our recent paper [7] that \( \alpha \) corresponds to the area ratio of OR in the sample.

In figure 2(b) we show the readout voltage \( V(t)/V^\infty \) generated responding to the dc drive yielding \( V(t \to \infty)/(= V^\infty) = 100 \mu V \) for the same input vortex configuration as studied above (figure 2(a)); i.e., the configuration formed by the ac drive with \( d_{\text{imp}} = 1 \mu m \) and \( V^\infty = 100 \mu V \) after \( n = 0 \) (red line), many cycles (\( n > 4000 \)) (blue line), and \( n = 100 \) cycles (green line). The horizontal dashed line again marks the position of 1. We observe qualitatively the same behavior as \( |V(t)|/V^\infty \) in figure 2(a), namely, a monotonic increase (red line), a monotonic decrease (blue line), and a nonmonotonic fast decrease followed by a slow increase (green line) to 1. Again, we find that the green line is reproduced by a weighted average of the red and blue lines. The purple line represents the fit of the green line to Eq. (1) with \( \alpha = 0.57 \pm 0.01 \). This value is close to \( \alpha = 0.60 \pm 0.04 \) obtained above. The result strongly suggests that we have indeed detected the intrinsic properties related to the vortex configuration not only from the ac readout, but also from the dc readout.

The characteristic time at which \( V/V^\infty \) shown by the green line in figure 2(a) takes a minimum is around \( t = 2 \) cycles, thus, corresponding to about 0.5 ms. This time roughly coincides with \( t = 0.5 \) ms around which \( V/V^\infty \) shown by the green line in figure 2(b) takes a minimum. Therefore, the characteristic time scales seen between figures 2(a) and (b) are nearly identical, insensitive to whether the readout is performed by ac drive or dc drive.

Obviously, a better fit is obtained by dc drive. However, this does not immediately mean that the ac readout experiment can be thoroughly replaced by the dc one. This is because the readout experiment by dc drive is applicable only when the initial and/or final configuration in the input experiment are highly disordered. This can be understood considering the fact that when both the initial and final configurations are relatively ordered, we are unable to perform the readout experiment that shows the dynamic ordering by using any dc drive. Conversely, the readout experiment by ac drive is applicable only when the initial and/or final configuration in the input experiment are relatively ordered. This is because when both the initial and final configurations are highly disordered, it is difficult to conduct the readout experiment that shows the dynamic disordering by using any ac drive [20, 21, 22], even with large \( d \) or small \( V^\infty \). In the present work, we have carefully selected the particular regions of the initial and final vortex configurations in the input experiment where both the dynamic ordering and disordering can be realized in the subsequent dc as well as ac readout experiment.

Now that we have established the readout technique by dc drive in addition to the ac one developed recently [7], we expect that both techniques will be applied complementarily to detect the vortex configuration over a wide range of disorder. The study using both techniques includes the determination of the vortex configuration during the dynamic ordering by dc drive, as mentioned in the introduction.

4. Conclusions

We study the random organization or dynamic ordering by ac drive using a vortex system of an \( \alpha \)-Mo\textsubscript{2}Ge\textsubscript{1-x} film with weak random pinning. We showed recently that the random organization by ac drive can be detected from the \( t \)-dependent voltage \( |V(t)| \) that increases and saturates to a steady-state value [7]. From the subsequent readout experiment of \( V(t) \) using various ac amplitudes \( d \), it was shown that the transient vortex configuration during the ac dynamic ordering is not microscopically homogeneous but consists of DR and OR. The area ratio of OR, \( \alpha(n) \), increases monotonically from 0 to 1 with increasing \( n \) [7].
In this work, we have developed an alternative readout method using a $dc$ drive. It is found that the $dc$ readout method gives the same results (e.g., the same value of $\alpha$) as obtained from the $ac$ drive. This finding provides an additional support for our view of the coexistence of OR and DR, and the interpretation of $\alpha$ [7]. We expect that these two methods will be used complementarily to detect the vortex configuration over a wide range of disorder, as well as to clarify the origin of the coexistence regions.

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