History dependent vortex configurations in superconducting disks of amorphous MoGe

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Abstract. We have investigated spatial configurations of vortices in superconducting disks of amorphous MoGe as a function of field history. Employing a scanning SQUID microscope technique, we observe quasi-symmetric distributions of the vortices imposed by the disk geometry. For a field cool measurement, a single vortex state appears after the Meissner state and it is followed by multi-vortex states at higher fields. In a zero field cool (ZFC) measurement, however, different behaviors are observed. On increasing magnetic field, the Meissner state switches directly to the multi-vortex state without showing the single vortex state. The corresponding magnetization curves of the disks are strikingly history dependent. These results indicate that the ZFC procedure results in an unusual penetration of the vortices in the small superconducting disks.

1. Introduction

Vortices confined into small superconductors, of which size is of order of the superconducting coherence length and/or the penetration depth, can have unique spatial configurations imposed by the sample geometry, via the influence of the screening current flowing along the sample edge [1-9]. For circular disk geometry the vortices are situated in a ring with symmetric spatial configurations with respect to the disk center, i.e., a pair of two vortices, a triangle of three vortices, and etc. Those configurations are proposed in numerical studies [2, 4] and also observed experimentally in Nb [8] and amorphous MoGe disks [9] by taking a field cool (FC) measurement, where the disks were cooled in magnetic field in order to ensure the equilibrium distributions of the vortices.

The issue of spatial configurations of the vortices in the disk geometry would be particularly interesting when magnetic field is varied after cooling the sample. In this case, the vortices enter (or exit) through the disk edge under the influence of a edge barrier. In this study we report direct observations of the vortices in superconducting disks of weak pinning, amorphous MoGe by a scanning superconducting quantum interference device (SQUID) microscope as a function of field history.
Figure 1. SQUID images of vortices in a MoGe disk with 34 µm in diameter measured by a field cool procedure in ≈ 3.4 K. The images of (a) and (b) were measured in fields of 10 and 12 µT, respectively. The image size is 64 × 64 µm² for each. Because of the weak pinning in amorphous MoGe disk, the vortex in (b) moved slightly during the image acquisition.

2. Experimental

We used an amorphous Mo₁₋ₓGeₓ film with x ≈ 0.22 sputtered on a silicon substrate on water cooled, rotating copper stage [10]. We patterned the film into many disks by lift-off technique. The diameter of the disks is 34 µm, which is about 80 times larger than the penetration depth λ(0) of 0.55 µm at T=0 of the MoGe film. The thickness d of the film is 0.3 µm. The superconducting transition temperature Tc is ≈ 6 K. The pinning properties of identical films were reported in Ref. [10]. We covered the disks by 0.1 µm thickness of SiO₂ film on top.

We used a commercial scanning SQUID microscope with a pick-up coil of 10 µm in diameter [7, 9, 11]. The spatial resolution of the microscope is ∼ 4 µm. The sample space is surround by µ-metal shield, resulting in residual magnetic field (ambient field) ∼ 0.1 µT. A coil wounded in our sample holder allows us to apply small magnetic field H perpendicular to the disks.

3. Results and Discussions

Let us show vortex images taken by the FC procedure. We applied magnetic field above Tc and cooled the disks down to ≈ 3.4 K. The images observed on one of the disks are shown in Figs. 1(a) and (b). At low fields (µ₀H ≤ 11 µT) magnetic field is fully expelled from the disk, exhibiting the Meissner state (see Fig. 1(a)). Estimating the magnetization of the disk by M = ⟨B⟩ − µ₀H with ⟨B⟩ being averaged field over the disk [7], we find that M is negative and it decreases (or the amplitude of M increases) linearly with field up to 11 µT. With further increasing field, the magnetization exhibits a jump, followed by a linear decrease with field. Here, a single vortex penetrates into the disk as imaged in Fig. 1(b). The sequence of the jump and the linear reduction of M continues for larger fields. Each jump of M accompanies the penetration of additional vortex in the disk and this results in a transition to a different state of multi-vortices in the disk. The spatial configurations of the multi-vortex states are quasi-symmetric with respect to the center of the disk (not shown), similar to the results in numerical simulations [2, 4]. Some images on different disks of amorphous MoGe were reported in Ref. [9].

Different behaviors are observed when magnetic field is ramped up after the zero field cooling (ZFC). Figures 2 (a)-(d) show a series of vortex images measured in one field trace. Cooling the disk to ≈ 3.4 K in the ambient magnetic field results in the Meissner state (see Fig. 2(a)). As magnetic field is ramped up to 12 µT (this field corresponds to the single vortex state for the FC measurement), no vortex penetrates in the disk (see Fig. 2(b)). Subsequent observations in
Figure 2. Vortex images in a 34 $\mu$m diameter disk measured by ramping field up after a zero field cool to $\approx$3.4 K. The images of (a), (b), (c) and (d) were measured in fields of the ambient field, 12, 25 and 26.25 $\mu$T, respectively. The size of each image is 64 $\times$ 64 $\mu$m$^2$. These are parts of a series of images taken in one field trace. Different magnetic fields show that this state persists up to 25 $\mu$T (see Fig. 2(c)). Note that in the field cooled disk three vortices with the triangular configuration appear at 25 $\mu$T (not shown). Thus, this difference indicates the influence of the edge barrier for the vortex entry into the disk.

A slight increase of magnetic field from 25 $\mu$T results in the entry of a few vortices in the disk. As shown in Fig. 2(d) the vortices enter from the top and also the bottom of the disk image. We note that the penetration of vortices is not artificial, since the image was taken by a series of line scans made from left to right, of which direction is different from ones for the vortex entry. Another field trace shows similar penetration of the vortices just above 25 $\mu$T and we do not observe the single vortex state.

Estimating magnetization of the disk from the images, we find that $M$ decreases linearly up to 25 $\mu$T and it seems to exhibit a huge jump around 26 $\mu$T (not shown). This is strikingly different from the result for FC. Thus, we may conclude that for the ZFC procedure the Meissner state switches directly to the multi-vortex state without taking the single vortex state in between.

4. Conclusions
We have presented the vortex images for the amorphous MoGe disks measured by the scanning SQUID microscope as a function of the field history. Quasi-symmetric distributions of the
vortices imposed by the disk geometry were observed in the FC measurement. In the ZFC measurement, however, we observed the different behaviors. On increasing magnetic field, the multi-vortex state appears after the Meissner state without showing the single vortex state, implying the important influence of the edge barrier for the vortex entry at the disk edge.

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