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Observation of single vortices by magneto-optical imaging

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Abstract

We have improved our magneto-optical imaging system and succeeded in observing single vortices in a type-II superconductor. In order to maximize the quality of differential magneto-optical images, noises from vibration and drift of the cryostat are suppressed by fixing the pumping line for He-flow and by using a cryostat with reduced thermal contraction of the cold stage. To obtain large signals from single vortices, we minimized the distance between the sample surface and the garnet film by utilizing the thermal contraction of Apiezon grease. All these improvements made it possible to observe single vortices in $NbSe_2$ single crystals using magneto-optical imaging at low magnetic inductions (~1 G).

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1. Introduction

In type-II superconductors, the magnetic flux penetrates the sample in the form of quantized strings called vortices in the unit of $\Phi_0 = 2.07 \times 10^{-7}\,\mathrm{G\,cm^2}$. In order to study magnetic properties of superconductors and vortex dynamics, several methods that enable us to observe single vortices have been developed: Bitter decoration [1], scanning Hall probe microscope [2], Lorentz microscope [3], scanning SQUID microscope [4], and magneto-optical imaging (MOI) [5]. Among these methods, MOI has the advantages of high temporal resolution and large observable area without scanning the sample surface, combined with the applicability to any superconductors with a flat surface. When we consider control of vortex motions and applications of superconducting materials to industry and vortices to electronic devices, resolving both macroscopic and microscopic dynamics of vortices in bulk samples will become important. Therefore a method that can observe

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the whole sample in real time will be needed. Since MOI has advantages described above, it is most suitable for such a purpose.

Here we report an improvement of our magneto-optical imaging system and successful observation of single vortices in $NbSe_2$ single crystals at low magnetic inductions (~1 G).

2. Experimental

MOI is the method that visualizes stray fields perpendicular to the sample surface through the Faraday effect in an indicator film mounted on the sample. A linearly polarized incident light passes through a garnet film with in-plane magnetization and reflected at the metallic layer located between the garnet and the sample. Polarization of the reflected light changes as a function of the field at the garnet. This field-induced component is extracted by an analyzer and detected by a cooled CCD camera to obtain spatial variation of the field. Since magnetic flux rapidly spreads out when it goes away from the sample surface, the most important point to observe single vortices is to minimize the gap between the garnet film and the sample surface. If the gap becomes large, the contrast and the resolution of the observed MO images remarkably deteriorate. Thereby single vortices become hardly discernible. To minimize the gap, we utilized pillars of Apiezon grease with almost the same height with the sample (see Fig. 1(a)). Owing to the large thermal contraction of the grease, the garnet film is attracted to the sample as the temperature decreases. To achieve better contact, we used samples with their surfaces flat and parallel to each other.

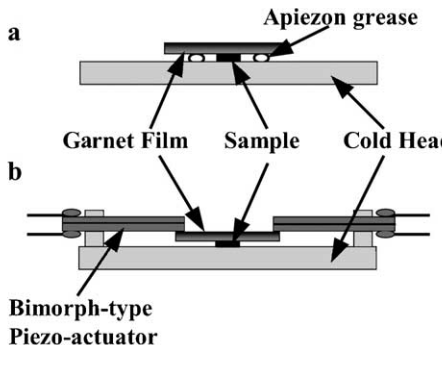

Fig. 1. Sketches of the setting of the sample and the garnet film with (a) Apiezon grease pillars and (b) adjusting mechanisms using bimorph-type piezo-actuators.

He-flow type optical cryostat (Oxford Instruments MicrostatHiResII) was used to cool the sample down to ~4 K. This cryostat is designed to reduce the vibrations from the pump and thermal drifts caused by the contraction of the cold finger. Both of these perturbations strongly influence the resolution and the quality of the MO images.

$NbSe_2$ single crystals were grown by iodine vapor transport technique using a two-zone furnace. The superconducting transition with $T_c = 7.2$ K and $\Delta T_c = 1$ K was measured by a SQUID magnetometer. The sample shows residual resistivity ratio $RRR \sim 50$, which indicates high quality of the sample to study vortex states. Flat surfaces needed for the MO observations were obtained by cleaving the crystal. Typical sample dimensions are $300 \times 300 \times 10\ \mu m^3$ with the shortest direction parallel to the *c*-axis. Since $NbSe_2$ has an easy-to-cleave property, we can easily obtain flat surfaces needed for MOI.

3. Results and discussion

Fig. 2(a) and (b) show the differential MO images in a single crystal of $NbSe_2$ at $T = 4.3$ K: background images obtained at $T = 8$ K (above T_c) are subtracted from the raw images. The images shown in Fig. 2(a) and (b) are averaged over 500 and 100 differential images to achieve higher signal to noise ratio, respectively. The dark area of roughly triangular shape corresponds to the diamagnetism of the sample. In addition to the dark areas, we can see a lot of small bright spots inside the sample. As is clear in the comparison between images (a) and (b), these small spots move as the field is changed. On the other hand, two large bright spots at the lower side of the sample do not change their positions because they are originated from defects in the garnet film. Simple estimation of the inter-vortex spacings, assuming a square lattice, gives 4.9 μm and 3.5 μm at magnetic inductions of 1 G and 2 G, respectively. The observed spacings match reasonably well with