Magneto-Optical Imaging System to Study Vortex Dynamics in High-$T_c$ Superconductor Devices

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Magneto-optical imaging system was fabricated to observe magnetic field distribution in a high-$T_c$ superconducting device. The performance of the fabricated system was checked by the preliminary experiments using a magnetic stripe card at room temperature and Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO) single crystal at 80 K. In the measurements using BSCCO, we have succeeded in the observation of magnetic flux line distribution with a spatial resolution of about 2.5 $\mu$m. Furthermore, a characteristic one-dimensional alignment of magnetic fluxes line along the crystal $a$-axis was observed in a half-peeled thin BSCCO flake region.

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I. INTRODUCTION

The vortex states in high-$T_c$ superconductors (HTS) have been much paid attention not only for scientific interests, but also for power or device application using HTS material. To shed light on the vortex states directly, several novel techniques have been developed [1], such as Bitter decoration method, [2, 3], scanning probe microscopy, [4–7], Lorentz microscopy and magneto-optical (MO) microscopy, [8–10]. Among them last two methods has the ability for the direct observation of motion and distribution of vortices.

On the other hand, high-speed superconducting devices using quantized vortices, such as a Single Flux Quantum (SFQ) logic circuit and a Superconductor Vortex Flow Transistor (SVFT) etc., have been developed. [11–13]. In the fabrication process, real-time observation of magnetic field and quantized vortices generated in the electric circuit should be very useful to produce a well designed device with high performance.

In the present study, to investigate the magnetic field distribution in a HTS device, a MO-imaging system has been fabricated. The advantage in the use of a MO microscope is its simple composition using the Faraday effects, compared to the Lorentz microscope.

In this paper, the detailed system composition of the fabricated MO-imaging microscope and the preliminary experimental results using a magnetic stripe card and Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO) single crystal sample are reported.
II. EXPERIMENTAL DETAILS

In this study, a MO-imaging system was composed on a broadboard using optical parts as shown the schematic diagram in Fig. 1. The system is composed of a light source, condenser lens, irises, dielectric interference filter, beam splitter, polarizer, analyzer, CCD camera, and monitor. As the light source, a metal halide lamp with a power of 250 W was used. By filtering the visible light using a dielectric interference filter, the light with wavelength of $\lambda = 546$ nm was illuminated as the incident light to the sample. The reflected light from the sample surface was detected by a CCD camera after being polarized by an analyzer. A home-use digital CCD camera (Nikon COOLPIX 4500) was used as the detector. High spatial resolution can be attainable by optimizing the optical path and optical parts, if we ignore the time for the optical alignment. For high sensitive observation, we can change the spot size and intensity of the incident light by arranging the positions of two irises without changing the focus condition.

In MO-imaging, since magnetic flux distribution can be observed by polarizing the incident and reflected light by Faraday effects at the local penetration region of magnetic fluxes, the sensitivity of the Faraday indicator is very important. For sensitivie measurements, we used Bi-substituted rare earth iron garnet film (MITSUBISHI GAS CHEMICAL Company) with thickness of about 10 $\mu$m grown by liquid phase epitaxy on GGG single crystal substrate as the Faraday indicator, and the garnet film was directly set on sample surface without any reflection film. The garnet film has a large Faraday rotation factor of about 0.9 deg-Oe$^{-1}$-$\mu$m$^{-1}$ (at $\lambda = 780$ nm).

To evaluate the performance of the fabricated MO-imaging system, magnetic stripe lines of a magnetic card and magnetic field penetration into BSCCO single crystal were observed. The BSCCO single crystal was grown by Traveling Solvent Floating Zone (TSFZ) method, and it showed an onset temperature of $T_c$(ON) = 92 K and critical temperature of $T_c$(R=0) = 82 K. In the present study, thin crystal sample of about 10 $\mu$m-thick was
III. RESULTS AND DISCUSSION

In the measurement using a magnetic stripe card, the garnet film was put on the card directly at room temperature. Fig. 2 shows a MO-image of the magnetization pattern in the card. In this image, bright and slightly dark stripe regions correspond to magnetic fields. Cleaved out from a single crystal rod.

In the measurement using BSCCO single crystal flake, the sample was at first zero-field cooled down at 67 K, and then magnetic field was applied to the sample along the crystal c-axis. For the magnetic field generation, we used a home made electro-magnetic coil made of copper wire of 500 µm-thick.

Fig. 3(a) shows the observed magnetic flux distribution pattern in the sample at 80 K with applied magnetic field of about 160 Oe. It can be seen that magnetic fluxes penetrate mainly in the right side of the sample. Fig. 3(b) shows an optical microscope image of the sample observed without the analyzer. It can be seen that there exist some half-peeled region in the right side of the crystal surface. This image shows that the magnetic flux penetration occurs only into the thin half-peeled region. Furthermore, we can see in the image that the magnetic fluxes one-dimensionally penetrate into the flake region nearly along the crystal a-axis. The origin for the one-dimensional structure will be discussed elsewhere [14].

On the other hand, the inset of Fig. 3(a) shows a line profile of intensity of the polarized light along the insertion line AB in the image of Fig. 3(a). As shown here, the spatial resolution of the fabricated system is evaluated as about 2.5 µm. Using the MO-
FIG. 3: (a): MO-image of magnetic flux penetration with magnetic field of 160 Oe. The image shows that magnetic flux penetrates only into the thin flake region nearly along the a-axis. The inset of Fig. 3(a) shows a line profile of intensity of the polarized light along the insertion line AB in the image of Fig. 3(a). As shown here, the spatial resolution of the fabricated system is evaluated as about 2.5 \( \mu \text{m} \).

(b): Optical image of the sample. There exist some half-peeled region in the right side of the crystal surface.

imaging system, evaluation of magnetic field distribution in HTS devices will be carried in near future.

IV. CONCLUSION

We fabricated and evaluated a MO-imaging system. Using the system, we have succeeded in the observation of magnetic flux distribution pattern in BSCCO single crystal with spatial resolution of about 2.5 \( \mu \text{m} \). Furthermore, we observed a characteristic one-dimensional alignment of magnetic fluxes along the crystal a-axis in the half-peeled thin flake region of BSCCO. These obtained data show the potential of the fabricated system to be available for the evaluation of magnetic field distribution in HTS electronic devices.

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