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Observation of quantized magnetic flux by electron holography

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The invited talk was given by A. Tonomura.

Quantized magnetic fluxes (fluxoids) are directly and quantitatively observed by electron holography. The magnetic lines of force of an individual fluxoid penetrating a superconductor are directly observed as an electron interference micrograph. This reveals not only the quantized flux value $h/2e$, but also the spatial distribution of a single fluxoid.

1. Introduction

A fluxoid penetrating a superconductor plays an important role in both the fundamental mechanisms and practical applications of superconductivity. Because fluxoids [1] are shaped like extremely thin filaments and have a small value, $h/2e$ ($=2\times10^{-15}$ Wb), much effort has been expended on developing methods to observe them. For example, in the Bitter technique [2], magnetic powder is sprinkled on the superconductor surface. The powder accumulates at the fluxoids, and the image is observed by electron microscopy. More recently, Mannhart et al. [3] observed the images of fluxoids trapped in a Josephson tunnel junction by measuring the Josephson current. This was done by scanning the junction surface with an electron fine probe. Hess et al. [4] observed a vortex lattice by detecting the difference in the electronic state between normal and superconducting states with a scanning tunneling microscope.

As desribed in this paper, the authors attempted to observe the flux value, polarity and microscopic distribution of a single fluxoid through holographic electron interference microscopy [5]. Fluxoid observation has been theoretically investigated, based on the fact that an electron beam is deflected or phase-shifted by magnetic fields [6–8]. However, only the location of a single fluxoid could be detected as a line of dislocations of parallel electron interference fringes by half of its spacing [9, 10]. This is due to the small flux value of a fluxoid. Using holography, magnetic lines of force can be directly observed as countour fringes in flux units of h/ne (n is the amplification rate of electron phase) in an electron micrograph. This technique will open up new possibilities for observing the dynamic behavior of fluxoids and their inner structures.

2. Experimental methods

Electron holography [11] is a two-step imaging method using electrons and light, as shown in fig. 1.

First, a field-emission electron microscope provides a coherent electron beam. The electron beam scattered by a specimen is recorded on film in an interference pattern known as a hologram. The electron wavefront is then reproduced as a light wavefront by laser beam illumination on the hologram.

With the stage now on an optical bench, optical techniques can perform operations that were impossible with the electron microscope. For

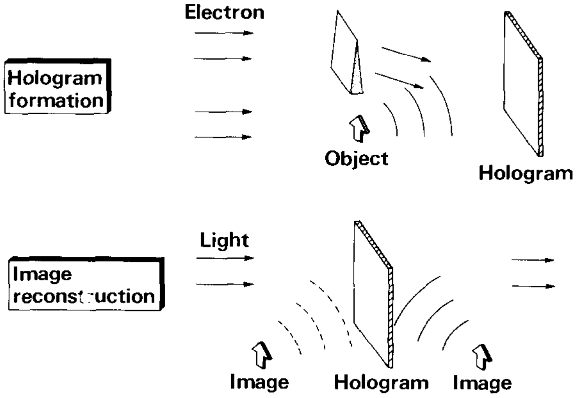

Fig. 1. Principle of electron holography.

example, only electron intensity can be observed by electron microscopy. However, electron phase distribution can also be observed as an interference micrograph by overlapping an optical plane wave with the reconstructed image in the optical stage of holography. When a technique peculiar to holography is used, a phase-amplified interference micrograph can be obtained [5]. In holography, in addition to the original image, a conjugate image, which has the amplitude of the complex conjugate, is produced as shown in fig. 1. In holography, as opposed to an interference microscope which produces an interference pattern of a plane wave and a reconstructed image, the conjugate image can be superimposed instead of a plane wave. Therefore, the phase difference is exactly doubled, and the phase is amplified. By repeating this process the amplification can be increased. Currently, the phase of an electron beam in the order of a hundredth of a wavelength can be detected [12].

With a magnetic specimen, phase contour fringes are proven to follow magnetic lines of force in flux units of h/e [13].

3. Experiments

The experimental arrangement is shown in fig. 2. Lead is evaporated onto one side of a thin tungsten wire. A magnetic field of up to several gauss is applied to the lead film. The specimen is cooled to 4.5 K. In a weak magnetic field, magnetic lines are expelled from the superconductor by the Meissner effect. If the magnetic field becomes strong, the magnetic lines penetrate the film in the form of fluxoids. Using electron beam illumination on the specimen from above, we observed the magnetic lines of force through the electron holography process.

The results are shown in fig. 3 [14]. This is an interference micrograph, that has been phase-amplified twice. Here, one contour fringe corresponds to one quantized flux $h/2e$. A single

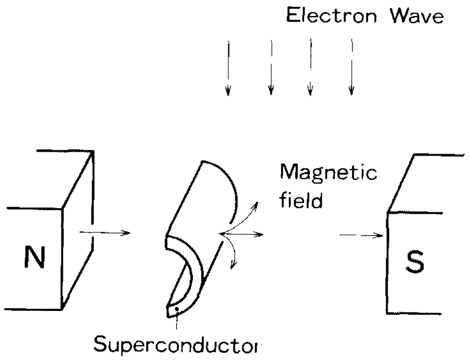

Fig. 2. Experiment of flux quantum observation.

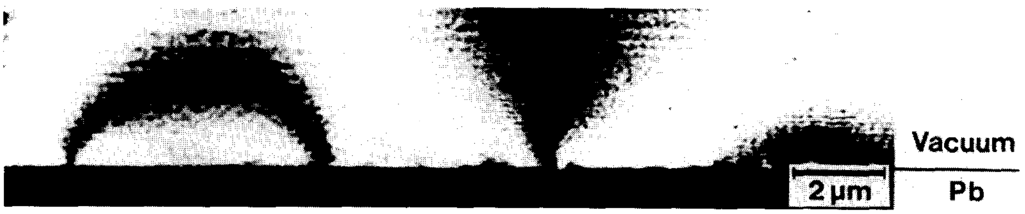

Fig. 3. Magnetic lines of force penetrating lead film (0.2 μm thick; phase difference amplification: ×2).

fluxoid has been captured in the right part of this photograph. The magnetic line of force is produced from an extremely small area of the lead surface. It then spreads out into free space. To prove that the observed magnetic line definitely indicates a fluxoid, the following experiments were performed.

When the specimen temperature exceeded the critical temperature, the magnetic line disappeared. This is because the superconducting state is destroyed, causing the vortex current to stop flowing. This offers proof that the observed magnetic line was generated by the superconducting vortex current.

Further proof was provided when the observed magnetic line persisted after the applied magnetic field was removed. Thus, the observed line was not due to the applied magnetic field.

In addition to isolated fluxoids, an antiparallel pair of fluxoids, connected by magnetic lines of force, was observed (fig. 3, left). The film thickness was 0.2 μm. This pair may have been created when the film was cooled through the Kosterlitz–Thouless regime [15] just below the critical temperature. Its presence is expected from the two-dimensional character of the thin film.

The effects of increased film thickness are now examined. The magnetic lines of force, when thickness is 1 μm, are shown in fig. 4. It can be seen that the state is completely changed. Magnetic flux penetrates the superconductor in a bundle; not individually in a fluxoid form. The figure does not show any of the fluxoid pairs.

Our explanation for this phenomena is as follows. Since the lead belongs to type-I superconductors, a strong magnetic field destroys the superconductive state in some parts of the specimen (intermediate state). The magnetic lines of force penetrate the specimen parts where superconductivity is destroyed as shown in fig. 4. However, since the other surrounding parts are still superconductive, the total amount of penetrating magnetic flux is an integral multiple of a quantized flux $h/2e$.

Thin film (fig. 3) was an exception. In this case, lead behaves like a type-II superconductor and the flux penetrates the superconductor in the form of an individual fluxoid.

4. Conclusions

Electron holography has opened a new way to quantitatively observe the magnetic lines of force of individual fluxoids penetrating a superconductor. This method is expected to help clarify fundamental problems in superconductivity such as pinning and high-temperature superconducting mechanisms.

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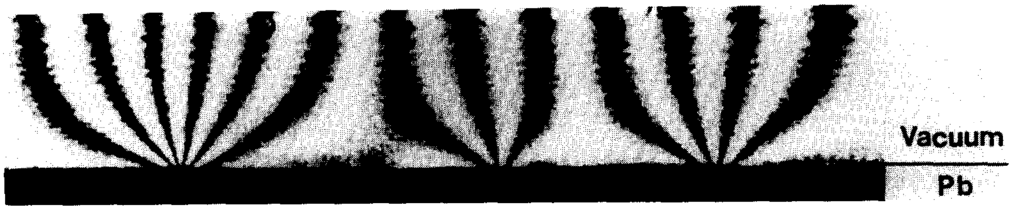

Fig. 4. Magnetic lines of force penetrating lead film (1.0 μm thick; phase difference amplification: ×2).

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