Computer Reconstruction from Electron Holograms and Observation of Fluxon Dynamics

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The customary optical reconstruction can be replaced with digital computations to dynamically and quantitatively observe microscopic magnetic fields. Electron holograms of time-varying fields are first recorded on videotape. Next, each hologram is reconstructed and phase amplified by computation. Interference micrographs are then reedited on the videotape. Using this method, the movement of fluxons trapped in a thin superconductive film of lead are observed for the first time near the critical temperature. The fluxon diameters on the surface look thicker when the sample temperature is raised from 5 K. Fluxons then begin to move near 7 K and finally disappear at the critical temperature 7.2 K.

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Quantized magnetic flux (fluxon)[1] plays an important role in both the fundamental and the practical aspects of superconductivity. For example, the critical current of a superconductor depends on fluxon dynamics, i.e., how fluxons can be fixed at some pinning centers around the current level. A fluxon is shaped like an extremely thin thread unobservable even by optical microscopy. In addition, it has a very small magnetic flux, $h/2e$ ($=2\times10^{-15}$ Wb). For static observation, the Bitter method[2] has often been used. Here, magnetic powders sprinkled on superconductor surfaces and accumulated at fluxons are observed by electron microscopy. However, up to now no methods have been available to dynamically observe fluxons.

Recently, new methods[3] have been developed for fluxon observation. From these, we used electron holography to directly and quantitatively observe magnetic lines of force of a single fluxon[4] based on the Aharonov-Bohm effect,[5] without recourse to its static replica. Thus, this provides us with a new possibility to observe the dynamical behavior of fluxons.[6]

Electron holography[7] is a two-step imaging process. An electron interference pattern (hologram) between an object wave and a reference wave is first recorded in an electron microscope, and then the object image is reconstructed by laser-beam illumination onto the hologram. The exposure time for the recording is determined from the electron-beam brightness and the sensitivity of the photographic film. Note that it is at least a few seconds.

In the present experiment, we have attempted to use dynamic electron holography with video instead of a photographic system. The experimental arrangement is shown in Fig. 1. An electron interferogram (hologram) was formed in a 150-kV field-emission electron microscope[8] in which a Möllenstedt-type electron biprism[9] was installed. The interferogram was dynamically observed with a TV camera (Gatan) and recorded on videotape. The object magnification ranged from 10000 to 30000 times on a 20-cm monitor display. The video signal from the tape was digitized and stored in a memory device with 512 frames (max), and then transported frame by frame to the Appollo DN 10000 computer.

The electron phase distribution was numerically computed by the computer from the hologram recorded in each frame by the Fourier transform method,[10] and was displayed as a phase-amplified (2×) contour map[11] in units of half an electron wavelength. Since a magnetic flux of h/e produces a phase shift of 2π between two electron waves enclosing the flux, one contour corresponds to the magnetic line of force from a single fluxon, $h/2e$.[12]

The quality of the resultant contour map was poor compared with that of conventional maps reconstructed from holograms recorded on film. This was inevitable for dynamic observation because the exposure time for taking an electron hologram was as short as $\frac{1}{30}$ s, and also because the number of carrier fringes in the hologram was as small as 10–50.

Therefore, to eliminate some deterioration, such as that due to Fresnel fringes produced from the biprism wire edges, we made use of the fact that the objects here

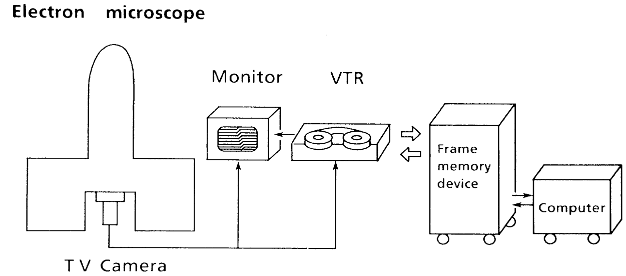

FIG. 1. Experimental arrangement for dynamic electron holography.

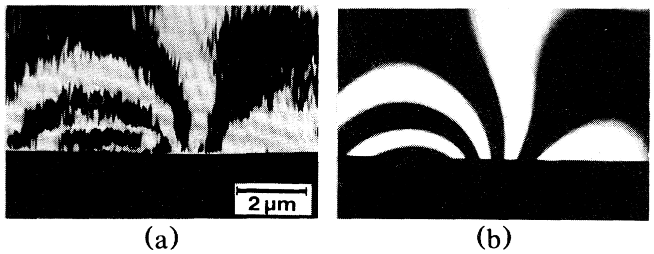

FIG. 2. Interference micrographs of trapped fluxons (phase amplification, 2×). (a) Original micrograph. (b) Processed micrograph.

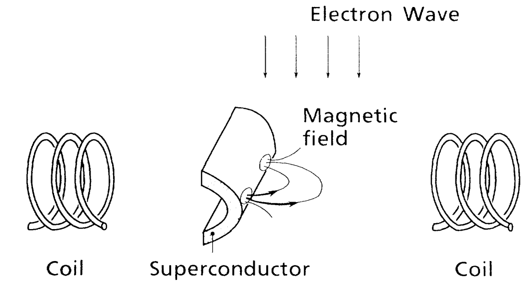

FIG. 3. Experimental arrangement for observation of fluxon bundles trapped in a superconductor.

were magnetic fields; magnetic fields in a vacuum cause phase distributions with harmonic-function shapes. Details of the numerical reconstruction and the image processing will be reported elsewhere.[13]

An example of a reconstructed contour map is shown in Fig. 2(a) and a computational improvement of it in Fig. 2(b). Evidently, the processing removes only noise and does not introduce any artifacts. Contour fringes here can be interpreted as magnetic lines of force in $h/2e$ flux units,[12] since the map is phase amplified 2 times. The direction of the flux can be determined from the corresponding interferogram. One can observe at a glance how magnetic flux trapped inside a superconducting Pb film leaks into the vacuum.

An arrangement for fluxon observation is schematically shown in Fig. 3.[4] A thin tungsten wire 30 μm in diameter was cleaned and smoothed by resistive heating, and lead, approximately 0.7 μm in thickness, was evaporated onto one side of it. This sample was first cooled down to 5 K at the liquid-He low-temperature stage in the electron microscope. It was confirmed by observing an electron interferogram on the TV monitor that there were neither magnetic fields not other disturbances such as electrostatic fields due to the charging effects. The sample temperature T was raised to around 8 K, just above the critical temperature $T_c=7.2$ K for lead, and then a magnetic field of 0.5–5 G was applied perpendicular to the lead film. Since the intermediate lens was employed for image focusing and the magnetic objective lens was not used in this experiment, there was no magnetic field component parallel to the film. When the sample temperature was recooled to 5 K, the magnetic fluxons were trapped in separately squeezed units, fluxon bundles,[14] by the superconducting lead film. The applied magnetic field was turned off to avoid even the slightest movement of the electron interference pattern during the observation due to the possible drift of the field-coil current.

The trapped fluxons remained stationary at 5 K as in our previous static observation.[4] When the sample temperature was again raised, the diameters of the fluxons gradually increased. After the fluxons began to move at $T \sim T_c$, the produced hologram was recorded on videotape for 10–20 min without a break. Since the fluxons kept still for a period and then suddenly moved, only a short scene of a few seconds including the flux change was selected and reconstructed numerically for observation as magnetic lines of force. The manner of flux changes was rather spontaneous and various: Fluxons appeared to move abruptly from one pinning center to another, to go and return between two pinning centers, and finally vanish when an antiparallel pair of fluxons attracted each other. When T exceeded T_c, all trapped fluxons disappeared.

Figure 4 shows the time variation of the flux shown in Fig. 2. One may notice two differences from our previ-

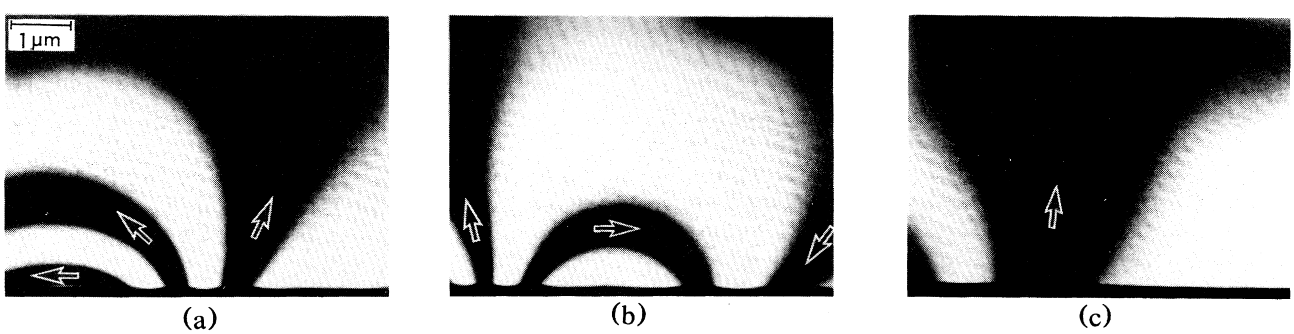

FIG. 4. Interference micrographs of fluxons trapped in superconducting lead film (phase amplification, 2×). (a) $t=0$ s. (b) $t=0.13$ s. (c) $t=1.33$ s.

ous static results[4] observed at 4.5 K with the magnetic field on, where the fluxons were in the same direction as the applied field and had thin necks on the sample surface. In the present case, however, most trapped fluxons were antiparallel pairs, and did not have thin necks. Thick necks result from the increase in penetration depth at $T \sim T_c$. Thicker necks may be due to the fact that the fluxons move into the shadow of the wire, and that the electron beam cannot pass through their true necks. Antiparallel pairs of fluxons may have been produced when a strongly pinned fluxon attracted an oppositely directed fluxon from the film edge so as to make the total magnetic energy smaller, since fluxons can move at $T \sim T_c$.

Photographs (a)–(c) in Fig. 4 show how the thermally excited flux behaves: Three fluxons in the upward direction (shown by arrows in the figure) are trapped in the center of Fig. 4(a), and three magnetic lines of force leak into the vacuum. At $t = 0.13$ s, the fluxons shift to the left corner of Fig. 4(b). It can be seen in the frame that two upward fluxons and two downward fluxons are connected by magnetic lines of force. At $t = 1.33$ s, only a single upward fluxon remains, thereby producing a broad magnetic line. Strictly speaking, since the flux change is completed after a lapse of 0.03 s, a single frame interval, the behavior of a specific flux cannot be followed. It can be followed, however, if the time resolution becomes high enough to catch transient states between the two frames before and after the change. Or, one can follow the flux movement in a wider field of view even if the resolution is insufficient.

An example of a lower-magnification observation is shown in Fig. 5. One can see the whole aspect of magnetic lines produced from up and down fluxons trapped at various locations of the superconductor. The flux dynamics can be explained here as follows.

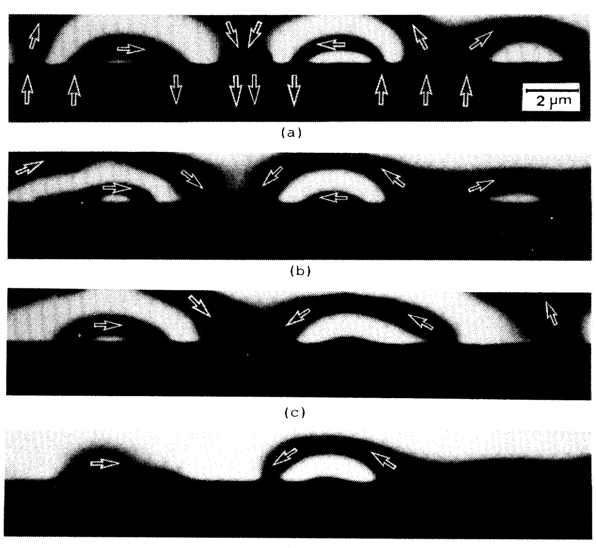

FIG. 5. Dynamic observation of fluxons trapped in superconducting lead film (phase amplification, 2×). (a) $t = 0$ s. (b) $t = 3.43$ s. (c) $t = 3.47$ s. (d) $t = 3.50$ s.

Fluxons remained almost stationary for 3 s in Fig. 5(a) and then suddenly moved within only 0.03-s intervals as seen in the three successive frames (b), (c), and (d). The U-shaped double magnetic lines in the central part in Fig. 5(a) hardly change. Here, only the inner magnetic line shrinks from frame (a) to (b). The U-shaped magnetic line in the right part changes slightly as shown in the figure, while the double magnetic lines in the left part almost disappear within only 0.03 s between frames (c) and (d), presumably by approaching and overlapping two antiparallel fluxons. Thermal energy must have excited the flux and allowed it to move over the pinning barriers.

In other cases, however, the flux change was faster and two interferograms (holograms) before and after the change were doubly exposed in a single frame. The resultant contour map appears to consist of two regions having two different flux distributions as shown in Fig. 6. This map results from the production of a Moiré pattern of the two interferograms. Planning is now under way for a new system to resolve such quick fluxon dynamics.

In conclusion, the present technique, electron holography combined with video recording and computer reconstruction, could open the way to dynamic observation of microscopic magnetic fields. For the first time, fluxon dynamics were actually observed with a time resolution as fast as $\frac{1}{30}$ s. In the near future, we will try to observe fluxon movements through electric-current injection in the hope that such direct observations will elucidate the flux-pinning mechanism, especially for high-temperature superconductors.

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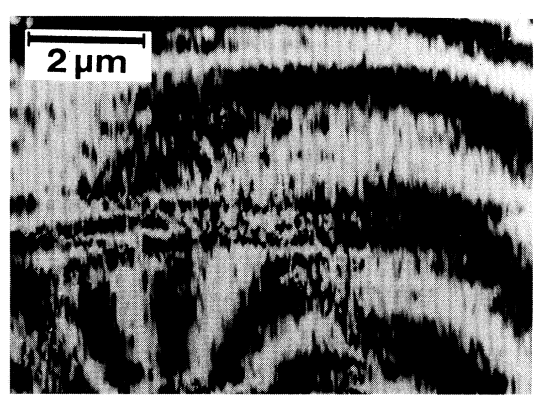

FIG. 6. Interference micrograph of fluxons in transit.

memory device and the Appollo DN 10000 computer.

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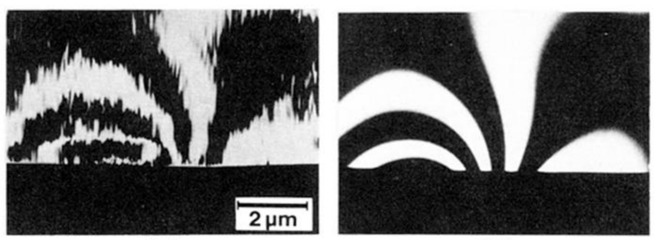
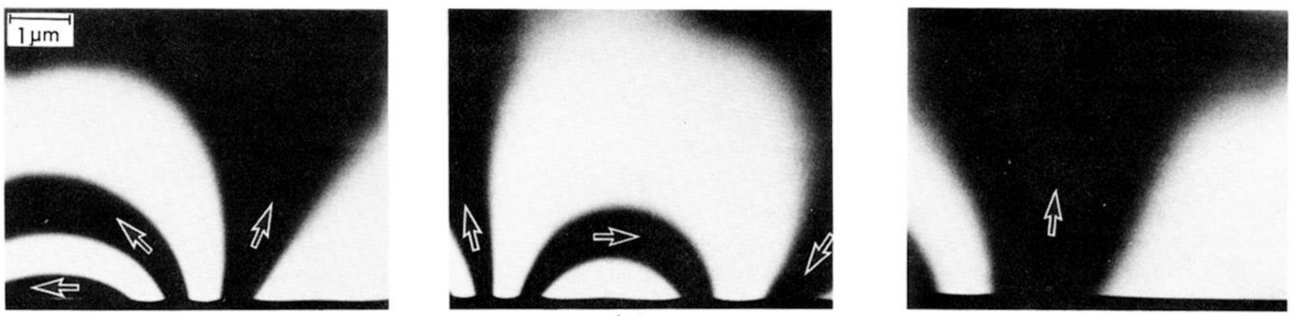


(a) (b)

FIG. 2. Interference micrographs of trapped fluxons (phase amplification, 2×). (a) Original micrograph. (b) Processed micrograph.



(a) (b) (c)

FIG. 4. Interference micrographs of fluxons trapped in superconducting lead film (phase amplification, 2×). (a) $t=0$ s. (b) $t=0.13$ s. (c) $t=1.33$ s.

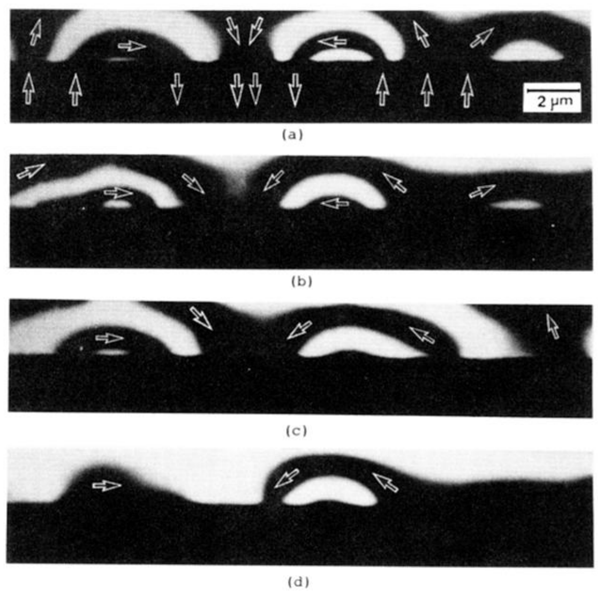
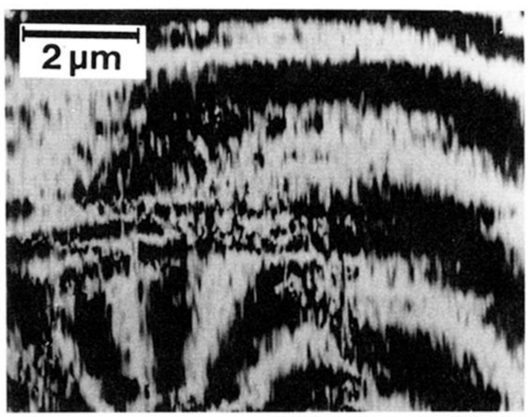


FIG. 5. Dynamic observation of fluxons trapped in superconducting lead film (phase amplification, 2×). (a) $t = 0$ s. (b) $t = 3.43$ s. (c) $t = 3.47$ s. (d) $t = 3.50$ s.



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