Nuclear Instruments and Methods in Physics Research A 601 (2009) 203–212

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Development of electron phase microscopes

Akira Tonomura [a,b,c,*]

[a] Hitachi, Ltd., Hatoyama, Saitama 350-0395, Japan
[b] RIKEN, Wako, Saitama 351-0198, Japan
[c] OIST, 12-22, Suzaki, Uruma, Okinawa 904-2234, Japan

ARTICLE INFO

Available online 10 January 2009

Keywords:
Electron holography
Electron phase microscopy
Field emission
Magnetic lines

ABSTRACT

We have developed electron–optical techniques such as those of bright and coherent electron beams and electron interference systems that have led to the realization of electron phase microscopy. Microscopes using these techniques have been used to carry out fundamental experiments in quantum mechanics once regarded as "Gedanken" experiments, to quantitatively observe magnetic lines of force (or equipotential lines) inside and outside ferromagnetic (or electric) samples in a form of holographic interference microscopy, and to dynamically observe individual magnetic vortices in superconductors by Lorentz microscopy. This paper is dedicated to Professor Kai Siegbahn, who passed away on 20 July 2007.

1. Introduction

Advanced technologies such as nanotechnology and biotechnology have progressed to the point where even atoms and molecules can be controlled. To advance them further, we need a better understanding of microscopic structures and electronic states of materials. The optical techniques used to obtain such understanding are no longer keeping up with the high-resolution needs due to the limit of the wavelength of light. Electrons are an attractive alternative since their wavelength can be as short as $\frac{1}{100{,}000}$th that of light. However, electron–optical techniques are not as fully developed as optical ones. For example, the lenses used in electron optics are subject to large aberration. Therefore, the resolution of electron microscopes is not limited by the wavelength but by lens aberration.

We started our research on electron holography in 1967 as a way to overcome the technological limits of electron microscopy. Electron holography is a two-step imaging method: an interference pattern between an object wave and a reference wave (hologram) is formed using electrons, and an optical image of the object is reconstructed by illuminating a light beam on hologram film. Since electron wavefronts are precisely transformed into optical wavefronts by an electron holography process, versatile solutions such as aberration correction are made possible by using optical techniques in the reconstruction stage.

After one year of experiments, we demonstrated that optical images without disturbance from their conjugate images can be reconstructed from electron holograms [1]. The first aim of our experiment, to show the feasibility of electron holography, was achieved. However, we did not realize Gabor's dream for electron holography [2], that aberrations in electron lenses can be compensated for by using electron holography and that individual atoms can be observed. The resolution of the reconstructed images obtained in our experiments did not reach even that of conventional electron microscopes due to the poor coherence of the electron beam available in those days [1].

We learned from our experiments that much brighter electron beams, like laser beams in optics, would be needed to realize new applications that are unobtainable with conventional electron microscopy. In 1968 we started to develop the bright and coherent electron beams needed for electron holography to become practical.

We demonstrated in due course that electron holography can be used not only for improving the resolution of electron microscopes, but also for observing microscopic distributions of electromagnetic fields by using the electron phase information. Contour lines in the phase distribution on interference micrographs were found to directly indicate the lines of force of magnetic fields [3] and the equipotential lines of electric fields [4]. For film samples of a uniform material, the contour lines were found to indicate the thickness contours of the samples [5].

In this paper, I describe the techniques we developed for electron phase microscopy, and their applications.

2. Apparatuses and techniques

2.1. Bright and coherent electron beams

2.1.1. Field-emission electrons

The most important technique for electron phase microscopy is the generation of bright and coherent electron beams. In 1967, we

*Corresponding author at: Hitachi, Ltd., Hatoyama, Saitama 350-0395, Japan.
E-mail address: akira.tonomura.zk@hitachi.com

0168-9002/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2008.12.201

started developing electron beams that are field-emitted from a pointed tip and have continued their development. The brightness of a field-emission electron beam can be higher than that of a conventional thermal emission electron beam by five orders of magnitude. Several groups attempted to use a field-emission electron beam as an electron source for electron microscopes in the 1950s, but they were confronted by technical difficulties. The first field-emission electron gun was developed for scanning electron microscopes in 1968 by Crewe et al. [6].

The biggest challenge in our development efforts was how to accelerate this inherently bright field-emission beam without degrading its brightness. The radius of the pointed tip is 1000 Å, but the virtual source diameter is as small as 50 Å since electrons are emitted radially. The source is thus easily blurred by lens aberration, which is inevitable during acceleration from a few kV to 100 kV or higher. In addition, the source is easily moved by mechanical vibrations of the tip relative to the microscope column, and by deflections of the electrons due to stray AC magnetic fields. If the source image is blurred or moved even by a fraction of its diameter, the effective beam brightness, or luminosity, of the electron beam is degraded. To eliminate such disturbances, we had to prevent even the slightest mechanical vibrations of the tip, the accelerating tube, and the microscope column and prevent the deflection of the fine beam due to stray AC magnetic fields.

2.2. An 80 kV field-emission electron gun

In 1979 we developed an 80 kV field-emission electron gun after 10 years of determined efforts [7] (see Fig. 1). Electrons are field-emitted from a single-crystalline tungsten tip. The ambient pressure is kept at 3×10^{-8} Pa to obtain a stable emission of 100 μA. The emitted electrons are accelerated at 80 kV through electrodes shaped to minimize aberration [8]. Special attention is paid to the mechanical stability of the tip relative to the microscope column and also to the magnetic shielding of the electron beam not only in the gun chamber but also in the electron microscope column, especially in the condenser lenses and specimen chamber.

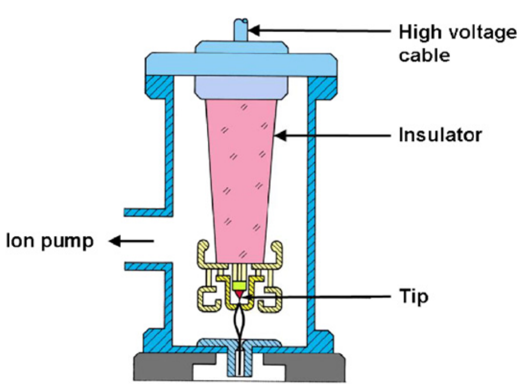

Fig. 1. 80 kV field-emission electron gun.

We obtained an electron beam two orders of magnitude brighter than the thermal emission beams used in those days (see Table 1). With this microscope, electron interference patterns became directly observable on a fluorescent screen, and as many as 3000 interference fringes could be recorded on film, one order of magnitude greater than the maximum number recorded up to that time. The resolution of reconstructed images became comparable to that available with electron microscopes [7], and information that had been inaccessible with conventional electron microscopy became obtainable by using electron holography, leading to several new applications. Among them, microscopic distributions of electric and magnetic fields were directly and quantitatively observed in holographic interference micrographs [3,4].

This brightness value, however, was still not high enough for "high-precision" electron phase microscopy. We needed a high-magnification hologram with a large number of carrier fringes in order to overcome the resolution limit of electron microscopes, and we needed a high-contrast hologram to reconstruct phase images with precision reaching $\frac{1}{100}$th of the electron wavelength. Since the beam brightness obtained was still restricted by both movement and blurring of the electron source and there was room to increase the beam brightness by two or three orders of magnitude in principle, we continued to develop even brighter field-emission beams.

We also recognized the need for higher acceleration-voltage electron beams. Conventional electron microscopic images can be observed if only electrons are transmitted through the film sample, though the resolution may be degraded a bit due to both inelastic scattering of the electrons and chromatic aberration of the electron lenses. In electron holography, however, the situation is different. Image formation is based on interference between two electron beams, one transmitted through a thin-film sample and the other through a free space (reference beam). If the electrons lose energy and coherence due to inelastic scattering, neither holograms nor reconstructed images can be formed. A specimen that permits electron microscope observation does not necessarily permit holographic observation. A specimen for holographic observation has to be thinner. This is why holography requires higher operating voltages than electron microscopy. We concluded that both brighter and faster electron beams were needed for practical application of electron phase microscopy.

2.3. Higher-voltage field-emission electron guns

The beam brightness, in general, increases proportionally with the acceleration voltage. However, it is difficult to apply a voltage higher than 100 kV to a single-stage acceleration system like that shown in Fig. 1. With a field-emission gun, the possibility of an electric discharge has to be eliminated since a discharge can

Table 1
History of development of bright & coherent electron beams.

Year	Electron microscope	Electron gun	Brightness (A/cm^2 · ster)	Application
1968	100 kV EM	Thermal emission	1×10^6	Experimental feasibility of electron holography [1]
1979	80 kV FEEM	Field emission	1×10^8	Direct observation of magnetic lines of force [3]
1982	250 kV FEEM	Acceleration tube: six electrodes	4×10^8	Conclusive proof of AB effect [12]
1989	350 kV FEEM	Ten electrodes	5×10^9	Dynamic observation of vortices in metal superconductors
2000	1 MV FEEM	Thirty-five electrodes	2×10^{10}	Observation of unusual behaviors of vortices in high-T_c superconductors [32]

FEEM: field-emission electron microscope.