1

Importance of Electromagnetic Field and Its Visualization

Transmission electron microscopy (TEM) has been widely utilized to clarify the microstructures of various functional materials. In addition to bright-field and dark-field imaging methods for observing various lattice defects [1–5], high-resolution TEM [6–10] has been used for direct observation of atomic arrangements projected along the incident electron beam direction. Such detailed atomic arrangements can now be observed with a resolution of less than 0.1 nm.

Scanning transmission electron microscopy (STEM) is commonly used for elemental mapping at the atomic level with a microprobe (diameter, less than 0.1 nm) and a beam scanning system [11–14]. Analytical electron microscopy with energy-dispersive X-ray spectroscopy (EDS) and electron energy-loss spectroscopy (EELS) have also been used for composition and electronic state analyses [15–19]. EELS studies can now be performed with an energy resolution of less than 0.1 eV by using monochromators.

To comprehensively understand a material's functionality based on coupling electric and magnetic properties, the electromagnetic fields should be characterized inside and around the material. Among the various TEM techniques, electron holography is unique in its ability to quantitatively visualize electromagnetic fields on the nanometer scale. Here, in relation to visualizing electromagnetic fields, we highlight the importance of the field concept in reference to Einstein and Infeld [20]:

> A new concept appears in physics, the most important invention since Newton's time: the field. It needed great scientific imagination to realize that it is not the charges nor the particles but the field in the space between the charges and particles which is essential for the description of physical phenomena. The field concept proves…
>
> …………
>
> The theory of relativity arises from the field problems…
>
> From "The Evolution of Physics" by A. Einstein and L. Infeld, Cambridge University Press, Cambridge, 2nd ed. (1978) p. 244.

If we bring a magnetic material near a U-shaped magnet, as in Figure 1.1a, we will feel a force between the material and the magnet. This phenomenon can be

Material Characterization using Electron Holography, First Edition. Daisuke Shindo and Takeshi Tomita.

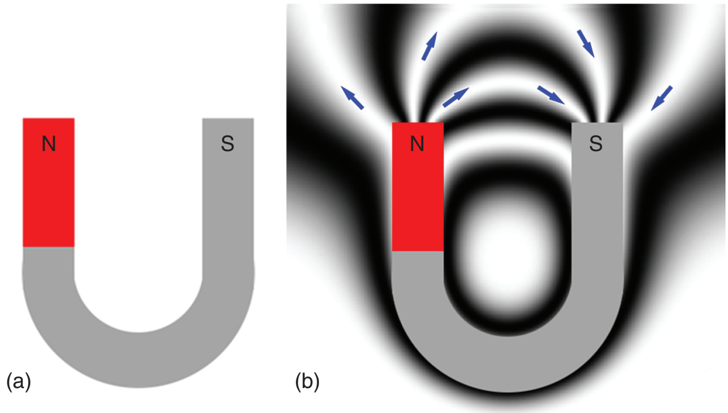

Figure 1.1 (a) U-shaped magnet. (b) Simulated magnetic field around magnet. Arrows indicate the direction of a magnetic flux.

explained by the existence of a magnetic field, which can be simulated as shown in Figure 1.1b.

Though a magnetic field cannot be observed with the naked eye or even with conventional microscopy techniques, it can be visualized using electron holography. Figure 1.2a shows a TEM image of a Co–Zr–O magnetic material [22]. The magnetic information can be recorded by first creating a hologram through the interference effect of incident electrons (Figure 1.2b). Then, by processing the hologram with a Fourier transformation, the magnetic fields both inside and outside the material can be directly visualized (Figure 1.2c). The importance of visualizing electric fields is discussed in Section 6.6.

Electron holography is thus a useful technique for directly visualizing electromagnetic fields. This book addresses the theory and application of electron holography, including the fundamental formulations of electromagnetic fields and relativity. The basic formulations of Maxwell's equations in relation to the special theory of relativity are presented in order to understand the formulation of electromagnetic visualization. The last section of this chapter covers the basic principles of TEM for the specific and detailed explanations of electron microscope hardware in the following chapters.

On the basis of these formulations and explanations, outlines of electron holography and the basic constitution of electron microscopes are explained in the former of Part II. Further detailed explanations of the hardware of transmission electron microscopes for electron holography with special instrumentation are presented in the latter of Part II.

Part III describes the extensive application of electron holography to various functional materials with respect to the principles and instrumentation of electron holography presented in Parts I and II. Techniques for visualizing and interpreting electromagnetic fields in and around materials are introduced for a wide variety

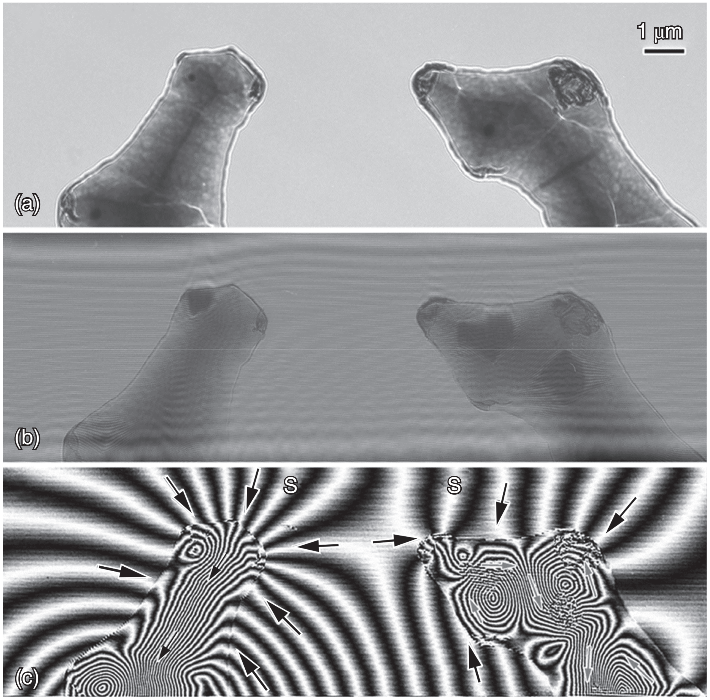

Figure 1.2 (a) TEM image showing two pieces of Co–Zr–O magnetic specimen. (b) Hologram obtained through interference effect of incident electrons. (c) Reconstructed phase image showing detailed magnetic fields both inside and outside the material. Image in (a) was observed under slightly defocused condition. Domain wall contrast (see Section 6.3.1) and absorption contrast due to thickness change appear. Source: Shindo and Akase [21], with permission from ELSEVIER.

of functional materials using a computer simulation. Part III also discusses the effectiveness of using advanced special attachments for in situ observation of electromagnetic fields in order to understand the electromagnetic properties of functional materials.

Part IV focuses on one of the most interesting applications of electron holography to visualize the motion of electrons. The stationary orbital formation and accumulation of secondary electrons around insulating materials, which depend on the material's surface morphology, can be visualized by detecting the fluctuations of the electric fields due to the motions of the secondary electrons. Furthermore, the magnetic flux due to electron spin polarization can be detected by applying an external magnetic field to the secondary electrons. Finally, on the basis of the theory of relativity, electron interference is interpreted using a "spinning linear wave" model proposed by the authors. With this model, the formation of electron interference fringes is successfully reproduced by simulation as a function of the number of incident electrons.

References

1 Hirsch, P.S., Howie, A., Nicholson, R.B. et al. (1977). *Electron Microscopy of Thin Crystals*. New York, FL: Robert E. Krieger Publishing Co. Inc.
2 Amelinckx, D.D.S., Landuyt, J., and Tenderloo, G. (1997). *Handbook of Microscopy*. Weinheim: VCH.
3 Cockayne, D.J.H., Ray, I.L.F., and Whelan, M.J. (1968). *Proceedings. 4 th European.Regional.Conference.Electron Microscopy*, 129. Vaticana, Roma: Tipografia Poliglotta Vaticana.
4 Howie, A. and Basinski, Z.S. (1968). *Philos. Mag. A* 17: 1039.
5 Cockayne, D.J.H., Ray, I.L.F., and Whelan, M.J. (1969). *Philos. Mag. A* 20: 1265.
6 Cowley, J.M. (1990). *Diffraction Physics*. New York: North-Holland.
7 Horiuchi, S. (1994). *Fundamentals of HREM*. Amsterdam: North-Holland.
8 Spence, J.C.H. (1988). *Experimental High Resolution Electron Microscopy*. New York: Oxford University Press.
9 Shindo, D. and Hiraga, K. (1998). *High Resolution Electron Microscopy For Materials Science*. Tokyo: Springer.
10 Spence, J.C.H. (1999). *Mater. Sci. Eng., R* 26: 1.
11 Pennycook, S.J., Berger, S.D., and Culbertson, R.J. (1986). *J. Microsc.* 144: 229.
12 Morishita, S., Ishikawa, R., Kohno, Y. et al. (2018). *Microscopy* 67: 46.
13 Shibata, N., Seki, T., Sánchez-Santolino, G. et al. (2017). *Nat. Commun.* 8: 15631.
14 Shibata, N., Kohno, Y., Nakamura, A. et al. (2019). *Nat. Commun.* 10: 2308.
15 Joy, D.C., Roming, A.D., and Goldstein, J. (1986). *Principles of Analytical Electron Microscopy*. Springer Science & Business Media.
16 Reimer, L. (1984). *Transmission Electron Microscopy: Physics of Image Formation and Microanalysis*. Springer.
17 Egerton, R.F. (1996). *Electron Energy-Loss Spectroscopy in the Electron Microscope*, 2e. New York: Plenum.
18 Williams, D.B. and Carter, C.B. (1996). *Transmission Electron Microscopy: A Textbook For Materials Science*. Springer.
19 Shindo, D. and Oikawa, T. (2002). *Analytical Electron Microscopy for Materials Science*. Tokyo: Springer-Verlag.
20 Einstein, A. and Infeld, L. (1978). *The Evolution of Physics*, 2e. Cambridge: Cambridge University Press.
21 Shindo, D. and Akase, Z. (2020). *Mater. Sci. Eng. R Reports* 142: 100564. https://doi.org/10.1016/j.mser.2020.100564.
22 Liu, Z., Shindo, D., Ohnuma, S., and Fujimori, H. (2003). *J. Magn. Magn. Mater.* 262: 308.