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Review article

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Nanoscale electromagnetic field imaging by advanced differential phase-contrast STEM

Satoko Toyama[1,2], Takehito Seki[1,2], Yuji Kohno[3], Yoshiki O. Murakami[1], Yuichi Ikuhara[1,4] & Naoya Shibata[1,4,5]

Abstract

Nanoscale electromagnetic fields formed at localized structures such as interfaces play a pivotal role in the properties of state-of-the-art electronic and spintronic devices. Direct characterization of such local electromagnetic fields inside devices is thus crucial for propelling their research and development. In recent years, direct electromagnetic field imaging via differential phase-contrast scanning transmission electron microscopy (DPC STEM) has attracted much attention. Recent developments of tilt-scan averaging systems and magnetic-field-free objective lenses have finally enabled the practical application of this technique to electronic and spintronic devices. This progress has led to the nanoscale, quantitative observations of electric fields of p–n junctions, 2D electron gas and quantum wells, as well as magnetic fields of magnetic domains, magnetic tunnel junctions and antiferromagnets. These studies demonstrate that DPC STEM can observe local electromagnetic fields from nanometre to sub-angstrom length scales across a wide range of materials and devices. In this Review, we describe the basic principles of DPC STEM, discuss its recent developments in both hardware and imaging techniques and finally show its practical applications in device characterization. We emphasize the immense potential of advanced DPC STEM for the research and development of future electronic and spintronic devices.

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Conclusions and outlook

[1]Institute of Engineering Innovation, School of Engineering, The University of Tokyo, Tokyo, Japan. [2]PRESTO, Japan Science and Technology Agency, Saitama, Japan. [3]JEOL Ltd, Akishima, Tokyo, Japan. [4]Nanostructures Research Laboratory, Japan Fine Ceramics Center, Aichi, Japan. [5]Quantum-Phase Electronics Center (QPEC), The University of Tokyo, Tokyo, Japan. e-mail: shibata@sigma.t.u-tokyo.ac.jp

Key points

- Differential phase-contrast scanning transmission electron microscopy has enabled electromagnetic field imaging at nanometre to sub-angstrom resolution.
- Recent developments in scanning transmission electron microscopy, such as the tilt-scan averaging system and magnetic-field-free lenses, have enabled the practical application of electromagnetic field imaging technique to electronic and spintronic devices.
- Nanoscale and quantitative observations of electric fields in semiconductor devices, including p–n junctions, 2D electron gas and quantum wells, have been achieved.
- Nanoscale magnetic domains, domain walls, switching of magnetization in magnetic tunnel junctions, and atomic antiferromagnetic layers have been visualized.
- Further developments of differential phase contrast, such as in situ biasing and magnetizing technique, will accelerate the research and development of state-of-the-art electronic and spintronic devices.

Introduction

Precise control of nanoscale structures such as interfaces is vital for future electronic and spintronic devices with higher efficiency, increased speed and smaller size. These nanoscale structures strongly correlate with local charge carriers and electromagnetic fields, which determine the properties and performance of the device. Hence, direct characterization of local charge carriers and electromagnetic fields in conjunction with nanoscale structures is essential for the research and development of future electronic and spintronic devices.

Scanning transmission electron microscopy (STEM) is a powerful tool for characterizing materials and devices at subnanometre dimensions. In STEM, a finely focused electron probe is scanned across a sample, capturing the transmitted and scattered electrons at each raster to obtain sample information. Advancements in aberration correctors have enabled the electron beam to be focused down to less than an angstrom[1–5], pushing the resolution of STEM beyond atomic dimensions. Additionally, STEM is distinctive in its versatile imaging modes. A schematic diagram of a typical STEM is shown in Fig. 1a. For atomic structure analysis, we use high-angle annular dark field (HAADF) for imaging heavy elements[6–8] and annular bright field (ABF) for imaging light elements[9–11]. We can obtain local information on elemental distribution and electronic states using energy-dispersive X-ray spectroscopy (EDS)[12] and electron energy loss spectroscopy (EELS)[13,14]. Moreover, recent technological developments in STEM bright-field detectors, such as segmented and pixelated detectors[15–26], have led to the development of new imaging modes. These include atomic structure imaging modes with ultrahigh signal-to-noise ratio for beam-sensitive materials: examples are optimum bright-field imaging[27,28] and electron ptychography[29–31], and the electromagnetic field imaging method using differential phase contrast (DPC)[32–36], which is the focus of this paper. A schematic diagram of DPC STEM is shown in Fig. 1b. DPC STEM detects the deflection of an incident electron beam by the electromagnetic fields of a sample using segmented or pixelated detectors, visualizing the electromagnetic fields at the nanometre or smaller length scale. DPC STEM enables not only high-resolution observations of electromagnetic fields but also simultaneous observation of atomic structures through other STEM imaging modes such as HAADF. An example of DPC STEM observation in a GaAs p–n junction is shown in Fig. 1c–g. In theory, diffusion and combination of electrons and holes at the depletion layer in between n-type and p-type regions induce electric fields pointing from n-type to p-type regions at the equilibrium state. Because the dopant concentrations in p-type and n-type regions are usually small (about 10^{17}–10^{19} atom cm^{-3}), there is almost no structural difference between the two regions. Therefore, almost no contrast appears at the p–n junction when using structure-sensitive imaging such as HAADF (Fig. 1g). DPC STEM clearly visualizes lateral electric fields from n-type to p-type regions, showing the exact position of the p–n junction. Many applications have also shown the usefulness of DPC STEM, such as imaging of electric fields in semiconductors[37–49], polar materials[50–56], atomic electric fields (even within single atoms)[50,57–59] and charge densities[60–65], and imaging of magnetic fields inside magnetic domains, domain walls[66–71] and magnetic skyrmions[72–76].

Recent advances in DPC STEM, particularly the development of tilt-scan-averaged DPC STEM (tDPC STEM)[48,77], have enabled quantitative observations of electromagnetic fields and charge densities in the vicinity of crystalline interfaces such as heterointerfaces and grain boundaries. Another noteworthy development is the magnetic-field-free objective lens[78], which enables high-resolution observation of magnetic materials in a magnetic-field-free environment. These advancements have led to real-space observations of 2D electron gas at wide-gap semiconductor heterointerfaces[79], magnetic domains and walls in polycrystalline magnets, magnetic fields in magnetic tunnel junctions[80] and atomic magnetic fields of an antiferromagnet[81]. Thus, the advanced DPC STEM has the potential to substantially enhance our understanding of device characteristics.

In this Review, we discuss the theoretical background of DPC STEM and recent developments of tDPC STEM and magnetic-field-free objective lenses. Then, we show the application of electromagnetic field observations using the advanced DPC STEM. Finally, we discuss the remaining challenges of electromagnetic field imaging and future directions of this field. Through the discussion, we show how DPC STEM might contribute to the research and development of future nanoscale devices.

Theoretical backgrounds of DPC STEM

In this section, theoretical principles of electromagnetic field imaging by DPC STEM are described. When an electromagnetic field exists perpendicular to the path of an electron, and the electron beam passes through the fields, momentum is transferred to the electrons and their phase will be shifted. The basic concept of DPC STEM is to measure this momentum transfer by splitting the detector on the diffraction plane and taking the subtraction of the intensities detected by the opposing detector segments. The idea of detecting phase information of the incident electron beam by subtracting electron intensities of the opposing detector segments was originally proposed by Rose[32,34]. Dekkers and de Lang substantiated that the differences in the electron intensities of the opposing detector segments correlate with the differential phase of the transmitted electrons, which relates to the electromagnetic fields inside the sample[33]. Waddell and Chapman[82,83]