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# Interferometric methods for mapping static electric and magnetic fields

## *Méthodes interférométriques pour cartographier des champs électriques et magnétiques statiques*

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ABSTRACT

The mapping of static electric and magnetic fields using electron probes with a resolution and sensitivity that are sufficient to reveal nanoscale features in materials requires the use of phase-sensitive methods such as the shadow technique, coherent Foucault imaging and the Transport of Intensity Equation. Among these approaches, image-plane off-axis electron holography in the transmission electron microscope has acquired a prominent role thanks to its quantitative capabilities and broad range of applicability. After a brief overview of the main ideas and methods behind field mapping, we focus on theoretical models that form the basis of the quantitative interpretation of electron holographic data. We review the application of electron holography to a variety of samples (including electric fields associated with *p*–*n* junctions in semiconductors, quantized magnetic flux in superconductors and magnetization topographies in nanoparticles and other magnetic materials) and electron-optical geometries (including multiple biprism, amplitude and mixed-type set-ups). We conclude by highlighting the emerging perspectives of (i) three-dimensional field mapping using electron holographic tomography and (ii) the model-independent determination of the locations and magnitudes of field sources (electric charges and magnetic dipoles) directly from electron holographic data.



RÉSUMÉ

La cartographie de champs électriques et magnétiques statiques avec une sonde d'électrons à un niveau de résolution et de sensibilité suffisant pour révéler des variations à l'échelle nanométrique requiert l'utilisation de méthodes sensibles à la phase, telles que la technique de l'ombrage, l'imagerie cohérente en mode de Foucault ou l'équation de transport de l'intensité (TIE). Parmi ces différentes approches, l'holographie électronique « hors axe » en microscopie électronique à transmission joue un rôle prépondérant, en raison de son caractère quantitatif et de son vaste domaine d'utilisation. Après une brève revue des principales idées et méthodes sous-jacentes, nous nous attacherons à décrire les modèles théoriques qui constituent le fondement de l'interprétation quantitative des données holographiques. Nous passerons rapidement en revue l'utilisation de l'holographie électronique pour étudier un grand nombre d'échantillons avec leurs champs électriques et

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magnétiques associés : jonctions $p$–$n$ dans les semi-conducteurs, lignes de flux magnétique quantifié dans les supraconducteurs, topographies du champ magnétique dans et autour de nanoparticules et autres… Les aspects relatifs aux géométries utilisées en optique électronique (doubles biprismes et dispositifs mixtes pour jouer sur la phase et l'amplitude) sont aussi mentionnés. Enfin, nous identifions plusieurs perspectives émergentes de grand intérêt : (i) la cartographie tridimensionnelle de champs en associant tomographie et holographie, (ii) la détermination de la position et de l'intensité de sources de champ (charges électriques et dipôles magnétiques) directement à partir des données holographiques.



## 1. Introduction

Recent improvements in the basic elements of the transmission electron microscope (TEM) are leading to a renaissance of the instrument, which is regaining a prominent role in the investigation of the nanoworld. These improvements include: (i) the development of Schottky and cold field emission electron guns with unprecedented brightness and coherence, (ii) hardware correction of lens aberrations and (iii) the availability of large semiconductor-based detectors that have single-electron sensitivity.

Significant changes have also resulted from the transition from rigid general-purpose microscopes (optimized for high-resolution work and structure analysis) to custom-made instruments that are designed to fit the needs of a particular research area. As a result, the most advanced research microscopes now play the role of versatile electron-optical benches, offering the option of inserting additional specimen stages and elements (such as electron biprisms, correctors and filters) at several locations in the column. This flexibility provides new exciting opportunities for the inventive researcher, especially for the investigation and mapping of electric and magnetic fields within and around the specimen at the superatomic or mesoscopic length scale. Such research has previously been hampered by the lack of flexibility of conventional TEMs.

In the first part of this paper, we discuss the phase-object approximation (POA), its limits of validity and theoretical models that have been developed for the interpretation of experimental data. Then, after a short review of the field mapping techniques and methodologies that have been proposed and developed over many decades, such as the Schlieren shadow technique and more recent approaches based on coherent Foucault (cF) imaging and the Transport of Intensity Equation (TIE), we focus on what we consider to be the superior technique: the TEM mode of image-plane or in-focus off-axis electron holography [1]. This method provides a unique capability for recovering both the amplitude and the phase of the object wavefunction. In this way, most of the information that is encoded in the electron beam by the specimen can be recovered, allowing projected electric and magnetic fields to be mapped quantitatively. Finally, we discuss the prospect of three-dimensional field mapping using electron holographic tomography and recently developed model-independent methods for determining the locations and magnitudes of field sources (electric charges and magnetic dipoles). In the present paper, we do not discuss non-interferometric techniques based on Lorentz TEM, which are described elsewhere, both in books, *e.g.* [2] and in review articles, *e.g.* [3].

## 2. The phase-object approximation and its limits of validity

The standard formulation of the phase-object approximation, whose derivation is presented in, *e.g.*, Ref. [4], leads to the representation of the electromagnetic field between planes $z_i$ and $z_{i+1}$ along the optic axis $z$ as a thin phase object, which is characterized by a transmission function $T$ that can be written in the form:

$$T(X,Y,z_i)=\mathrm{e}^{\mathrm{i}\phi(X,Y,z_i)}=\exp\left[\frac{\mathrm{i}\pi}{\lambda E}\int_{z_i}^{z_{i+1}}V(X,Y,z)\,\mathrm{d}z-\frac{2\mathrm{i}\pi e}{h}\int_{z_i}^{z_{i+1}}A_z(X,Y,z)\,\mathrm{d}z\right] \tag{1}$$

where the integrals are taken along a trajectory parallel to the optic axis (directed along the motion of the electrons), $V(X,Y,z)$ is the electrostatic potential, $A_z(X,Y,z)$ is the $z$-component of the magnetic vector potential $\mathbf{A}$ (which is linked to the magnetic induction $\mathbf{B}$ by the relation $\mathbf{B}=\nabla\times A$) and $e$, $\lambda$, $h$ and $E$ are the absolute values of the electron charge, the de Broglie electron wavelength, the Planck constant and the accelerating voltage of the electron microscope in the non-relativistic approximation, respectively. In order to include the whole field, the integration in Eq. (1) is performed between $-\infty$ and $+\infty$ and the $z_i$ coordinate can be taken to be coincident with the specimen or object plane. Relativistic correction can be included by using appropriate values for $\lambda$ and $E$. As the effect of tilting the plane wave is generally negligible at high incident electron energies, the transmission function in Eq. (1) holds for generic illumination. Moreover, the "absorption" of electrons in a very thick specimen or from large-angle scattering and subsequent cut-off by an aperture can be accounted for by introducing a real multiplicative amplitude term $a(X,Y)$ in the transmission function of the object in the form:

$$T(X,Y)=a(X,Y)\mathrm{e}^{\mathrm{i}\phi(X,Y)} \tag{2}$$