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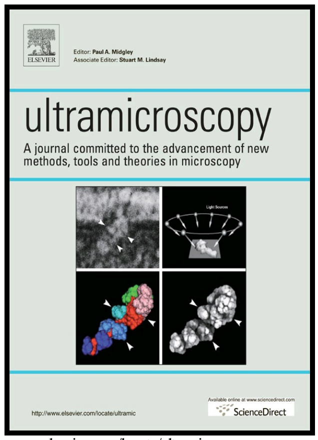

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Vadim Migunov, Christian Dwyer, Chris B. Boothroyd, Giulio Pozzi, Rafal E. Dunin-Borkowski

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Prospects for quantitative and time-resolved double and continuous exposure off-axis electron holography

Vadim Migunov[a,*], Christian Dwyer[a,c], Chris B. Boothroyd[a], Giulio Pozzi[a,b], Rafal E. Dunin-Borkowski[a]

[a]*Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons, Peter Grünberg Institute, Forschungszentrum Jülich, D-52425 Jülich, Germany*
[b]*Department of Physics and Astronomy, University of Bologna, viale B. Pichat 6/2, Bologna, 40127, Italy*
[c]*Department of Physics, Arizona State University, Tempe, Arizona 85287, USA*

Abstract

The technique of double exposure electron holography, which is based on the superposition of two off-axis electron holograms, was originally introduced before the availability of digital image processing to allow differences between electron-optical phases encoded in two electron holograms to be visualised directly without the need for holographic reconstruction. Here, we review the original method and show how it can now be extended to permit quantitative studies of phase shifts that oscillate in time. We begin with a description of the theory of off-axis electron hologram formation for a time-dependent electron wave that results from the excitation of a specimen using an external stimulus with a square, sinusoidal, triangular or other temporal dependence. We refer to the more general method as continuous exposure electron holography, present preliminary experimental measurements and discuss how the technique can be used to image electrostatic potentials and magnetic fields during high frequency switching experiments.

Keywords: Transmission electron microscopy, off-axis electron holography, double exposure electron holography, continuous exposure electron holography.

1. Introduction

The double exposure method in off-axis image plane electron holography was introduced by Wahl [1] as an electron-optical analogue of holographic interferometry, which involves the interference of wavefronts that have been reconstructed from two holograms on the same photographic plate [2, 3]. Wahl realised that it is convenient to make a separate recording of the interference fringe system without the specimen present [4] because the processing of the object and vacuum holograms on an optical bench (whether of the in-line or Mach-Zehnder type) allowed more versatility in the reconstruction step.

The re-introduction of double exposure electron holography (DEEH) by Matteucci and co-workers [5, 6] was prompted by the increasing application of off-axis electron holography to the investigation of long-range electromagnetic fields, which can extend from a specimen to influence the vacuum reference wave [7]. The moiré fringes that are visible when an object hologram and a vacuum reference hologram are superimposed [8] provide a faithful representation of the phase difference between the object wave and the reference wave (see [9] for a review). Similar moiré patterns have been obtained by the interference of three electron waves using a two biprism holographic setup in an electron microscope [10].

The use of charge-coupled device (CCD) cameras now allows the recording of successive off-axis electron holograms in perfect registry and their *a posteriori* analysis (see *e.g.*, [11]). Digital processing of superposed electron holograms to remove the carrier frequency can be used to increase the contrast of the equiphase fringes, while the superposition of two holograms taken with the object in opposite positions with respect to the biprism can be used to visualize electromagnetic fields with two-times phase amplification [12]. However, to date DEEH has only been used to study a small number of time-varying phenomena, such as ballistic emission from biased nanowires [13] and dynamic charge-related effects around biological specimens [14, 15].

Temporal resolution in off-axis electron holography has traditionally been determined by the speed of the detection system. Video-rate electron holography was realised in the early 1990s by the Tonomura group and used for the real-time observation of fluxon dynamics [16]. Although modern detector technology is able to improve temporal resolution to the ms or sub-ms level, phase errors (due to the low signal) then start to play a negative role [17]. A temporal resolution in the sub-μs range would permit studies of fast switching phenomena, such as magnetisation dynamics, with the nm spatial resolution that is offered by electron holography. Recently, DEEH was used to study the magnetic field of the writing head of a hard disk drive, showing its potential for high frequency applications [18].As we describe below, the technique offers further interesting prospects for ultrafast applications through the continuous acquisition of electron holograms of time-oscillating objects.

We begin by reviewing the original form of DEEH. We then extend the method to applications that involve exposing a detector continuously while the phase shift in the specimen changes, for example as a result of the time-dependent response of the

*Corresponding author
Email address: v.migunov@fz-juelich.de (Vadim Migunov)