Ultramicroscopy 157 (2015) 57–64

Contents lists available at ScienceDirect

Ultramicroscopy

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

Tunable caustic phenomena in electron wavefields

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ARTICLE INFO

Article history:
Received 14 January 2015
Received in revised form
6 April 2015
Accepted 9 April 2015
Available online 22 May 2015

Keywords:
Caustics
Transmission electron microscopy
Electron optics
Shaped electron beams

ABSTRACT

Novel caustic phenomena, which contain fold, butterfly and elliptic umbilic catastrophes, are observed in defocused images of two approximately collinear oppositely biased metallic tips in a transmission electron microscope. The observed patterns depend sensitively on defocus, on the applied voltage between the tips and on their separation and lateral offset. Their main features are interpreted on the basis of a projected electrostatic potential model for the electron-optical phase shift.

1. Introduction

Although they are ubiquitous in nature, optical caustics are intriguing phenomena that play an important role in fundamental and applied optics. In ray optics, caustics can be defined as those points in a wavefield where there is a coalescence of optical rays. At these points, ray optics predicts infinite intensity. In a wave picture, such divergences are tamed and caustics tend to correspond to points of high, but not infinite, intensity. The intensity in the vicinity of a caustic may exhibit complex interference effects, with correspondingly complex patterns occurring in the underlying optical phase (*e.g.*, phase dislocations and vortices). Surprisingly, despite the vast continuum of variations that can be made within an optical system, theoretical considerations show that a discrete classification of caustics is possible using catastrophe theory (see the papers of Berry [1,2] and the book of Nye [3] for a detailed review).

In electron optics, caustic patterns have been observed and utilized for many years in the transmission electron microscope (TEM) [4]. For example, they have been used to characterize quadrupole magnets in terms of electromagnetic lens focus [5], to study time-dependent magnetic fields [6], to measure lens aberrations [7] and to correct astigmatism [8], coma [9] and third-order aberration [10,11]. They have also been used to produce electron vortex beams [12] and Airy beams [13] in the TEM. Simple caustic phenomena have recently been observed in defocused bright-field TEM images of electrically biased carbon nanotubes [14–17] and metallic tips [18]. In the latter experiments, the tips were biased electrically with respect to significantly larger counter-electrodes and attention was focused on measurements of the electric fields surrounding them.

Here, we present a study of new caustic phenomena, which are formed by electron waves in vacuum and observed in defocused bright-field TEM images of two oppositely biased metallic tips. We show that these caustics can be controlled in a systematic way by varying the potential difference between the metallic tips, their relative positions and/or the image defocus. We also demonstrate good agreement between our experimental results and image simulations based on an idealized model of the electron-optical phase shift induced by the tips.

This paper is organized as follows. In Section 2, we describe our experimental setup. In Section 3, we begin by presenting results obtained when the image defocus is kept constant and the potential difference between the tips is varied. We then keep the potential difference constant and vary the defocus. In Section 4, we describe the theory used for our image simulations. In Section 5, the simulations are used to interpret our experimental results, including a description of the observed interference effects, using the language of catastrophe theory [3]. A discussion and conclusions are presented in Section 6.

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http://dx.doi.org/10.1016/j.ultramic.2015.04.003
0304-3991/

2. Experimental details

Two electrochemically etched needle-shaped tungsten tips were mounted in a NanoFactory scanning tunneling microscopy (STM) specimen holder, which comprises a micro-STM setup at the end of a single-tilt TEM specimen holder, as shown in Fig. 1(a). The holder, which is equipped with a piezo-driven STM tip and a sample mount, was used to apply a potential difference between the tips, as shown in Fig. 1(b). The potential difference between the tips, which were approximately collinear, set to be at the same height and observed out-of-focus, was used to create an electric field in the space surrounding them, which acted as a phase object for the electron beam. Interference patterns were recorded in the form of highly defocused bright-field images using an FEI Titan 60-300 TEM equipped with a high-brightness field emission electron gun, a Lorentz lens, a Gatan imaging filter and a 2048 $\times$ 2048 pixel charge-coupled device (CCD) camera. The microscope was operated at an accelerating voltage of 300 kV using non-standard lens excitations to provide an optimally wide field of view with high coherence and brightness. A schematic diagram of the setup is shown in Fig. 1(c).

3. Experimental results

3.1. Effect of potential difference at constant defocus

Fig. 2(a) shows a defocused bright-field TEM image of the two tips, for a separation between the ends of the tips of 0.9 μm and a nominal image defocus of -7 mm (*i.e.,* underfocus, with the objective lens of the microscope focused above the specimen), initially without a voltage applied between the tips. In this image, only Fresnel diffraction fringes around the two opaque tips are visible. The fact that the fringes around the tips have the same spacings confirms that the tips are at the same height in the microscope. Fig. 2(b) shows that an overlapping region is formed at the position of the negatively biased tip when a voltage of 40 V is applied between the tips. This region contains two-beam interference fringes inside it and a two-winged caustic at its end. In contrast, the wavefield at the position of the positively biased tip simply shows an enlarged shadow surrounded by diffraction fringes. The two regions of the wavefield look similar to those observed for a single tip in front of a planar electrode [18] and, at this stage, interact with each other weakly. Even though Fig. 2(b) was recorded at the same defocus as Fig. 2(a) without changing the settings of the projector lenses in the microscope, there is a slight change in magnification and a shift between the two images. The latter changes are thought to arise from the non-standard lens settings used, as well as from small changes in the excitations of the condenser lenses in the microscope. As a result of such unknown changes in magnification and image shift, scale bars are shown only for simulations and not for experimental images below.

Fig. 2(c) shows that the overlapping region at the position of the negatively biased tip widens and the two-beam interference fringe spacing decreases when the applied voltage is increased to 60 V. In addition, the two defocused images begin to interact, resulting in the creation of two high-contrast folds, with an increase in intensity and a fringe modulation where they cross. When the applied voltage is increased further to 100 V, a butterfly-like pattern develops, as shown in Fig. 2(d).

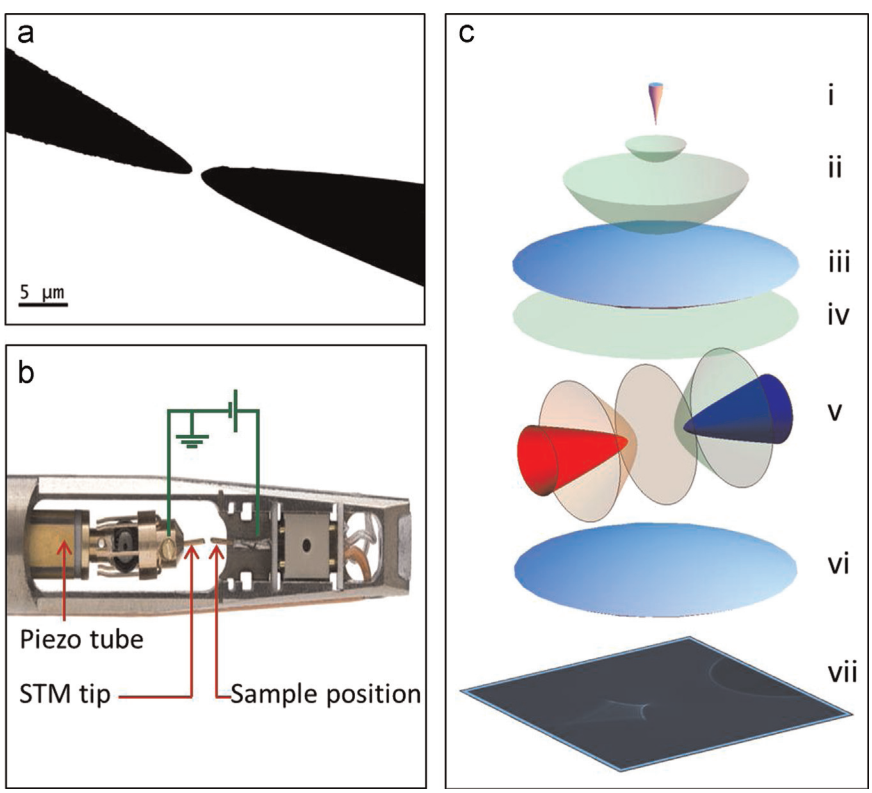

Fig. 1. Experimental setup. (a) Low-magnification bright-field TEM image of two electrochemically etched needle-shaped tungsten tips used to produce caustics in the TEM. (b) Photograph of the end of a NanoFactory STM specimen holder, in which the two tips were mounted on the STM tip and sample mount before inserting the holder into the TEM. (c) Schematic diagram of the electron-optical setup in the TEM, including (i) a field emission electron gun, (ii) a spherical incident electron wave, (iii) the condenser lens system of the microscope, (iv) a plane electron wave, (v) the biased tungsten tips, (vi) the magnifying lens system of the microscope and (vii) a bright-field TEM image recorded on a CCD camera.