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Lensless electron reflection microscopy using a coaxial point-source structure

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Abstract

A lensless image of the surface of a crystal is obtained by the reflection on this surface of a low-energy electron beam originated from a point source integrated in a coaxial structure. The point source is a sharp field emission tip and a free propagation of reflected electrons results from the shielding of the tip voltage provided by the coaxial structure. Images are obtained for an incidence angle between 3 and 45° and for nA incident currents with a kinetic energy down to 40 V. On silicon surfaces a magnification up to a few thousands and a spatial resolution of 100 nm are demonstrated.

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Keywords: Electron point source; Field emission; Lensless electron microscopy; Reflection electron microscopy

1. Introduction

Surface imaging methods based on elastic scattering of electron beams use various approaches from high-energy beams in grazing-incidence to low-energy beams in normal-incidence. Associated instruments, except in the case of simple low-energy electron diffraction designs, use lenses which lead to involved products. Recent experiments [1–3] were carried out in order to get rid of these lenses. The basic idea is to illuminate the surface by the divergent beam originated from an electron point source placed at a microscopic distance from the surface of a sample and to detect the elastically reflected beam on a screen placed at a macroscopic distance from the source (Fig. 1). Essentially this approach is the reflection analogue of the transmission method previously developed in the low-energy point projection microscope [4]. In that later microscope design, the point source is a field emission tip negatively biased and the grounding of the conductive sample provides at one and the same time the electron extraction field on the tip apex and a field free region for the transmitted electrons. In any attempt to use a similar design for reflection, a problem has to be tided over: reflected electrons come back towards the tip and their trajectories are bent towards the sample surface due to the negative voltage of the emission tip. If only secondary electron detection associated with scanning technique were used to image the surface, the effect of this negative voltage could be limited to a decrease of the detection efficiency [5,6]. But as long as elastic scattered electrons imaging is concerned, the problem cannot be reduced to a detection loss. Previous works already mention this effect without solving the problem. An approach taken by Mizuno is, by assuming a tip-sample geometry, to take into account the field effect on the image. Our approach is to provide an electrostatic shielding of the tip voltage for the reflected electron beam.

We first discuss why a micrometer scale control of this shielding is the main experimental challenge for lensless reflection microscopy. First a high enough resolution requires a short tip-to-sample distance and thus electrostatic shielding on this scale. Placed at 10 cm from the tip, an image detector with a 0.1 mm resolution (resolution of a

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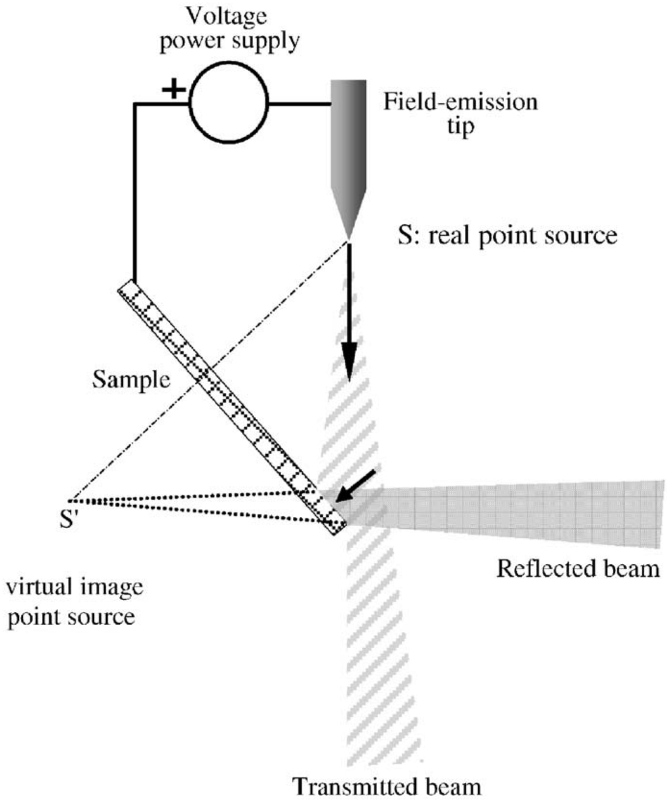

Fig. 1. Principle of projection microscopy using an electron point source. The edge of the sample can be seen either in transmission or in reflection. The arrows shows (not at scale) the electrostatic force on the electrons in the vicinity of the emitter apex and of the sample surface.

channelplate-screen assembly) limits the resolution on the surface to 1 μm for a 1 mm tip-to-sample distance. Thus sub-micrometer resolution on the surface requires 100 μm shielding. But if a high resolution is desirable for any microscope one has to realize that, in lensless reflection microscopy, this is a requirement for any correct imaging for most samples. The reason is that on a millimeter scale, the roughness of a crystal surface raises two imaging problems for this microscopy which aims to image flat surfaces. First are the reflections from disoriented areas in the field of view which overlap on the screen. Second is the intensity decrease which results from the addition of out of phase waves reflected from areas of parallel but random height terraces inside the first Fresnel zone defined on the surface from the tip. A direct consequence from the decrease of the source-to-sample distance is the decrease of the number of terraces in the illuminated area which is defined by the emission cone angle of sharp field emission tips [7] and is about 0.1 rd. Thus, a 10 μm diameter area is illuminated by a tip placed at 100 μm from the surface. For a disoriented area (Fig. 2) the decrease of the tip-to-sample distance d increases the angle α, this area is seen from the source. This reduces the overlap of its image with that of an adjacent flat area. A quantitative criteria is $\alpha > 2\,\mathrm{m}$ where m is the disorientation angle (relative to the terrace orientation). Introducing the distance between steps s, the step height h and the incidence angle i this criteria is $d < s^2 \sin^2 i/(2h)$ for small α values. Therefore for 45° incidence angle and atomic step size (~0.3 nm) sub-micrometer terraces are imaged for $d < 100\,\mu\mathrm{m}$. Concerning the out of phase wave addition problem, decreasing the tip-to-sample distance d decreases the size b of the region of the surface which contributes to constructive interferences at a given point of the screen. b is $(\lambda d)^{1/2}/\sin i$ (i.e. the intercept by the surface at an incidence angle i of the beam limited by the first Fresnel zone) where λ is the electron wavelength. This means that for a 100 eV electron beam at an incidence $i = 45°$, sub-micrometer resolution is obtained ($b \sim 0.2\,\mu\mathrm{m}$) for $d < 100\,\mu\mathrm{m}$. These considerations show that the use of lensless reflection microscopy requires to operate the tip at a short distance ($< 100\,\mu\mathrm{m}$) from the surface and therefore to provide shielding of the tip voltage on this scale. In addition appropriate surface preparation techniques to increase the flatness of the sample up to a distance between steps equal to a fraction of micrometer distance are required.

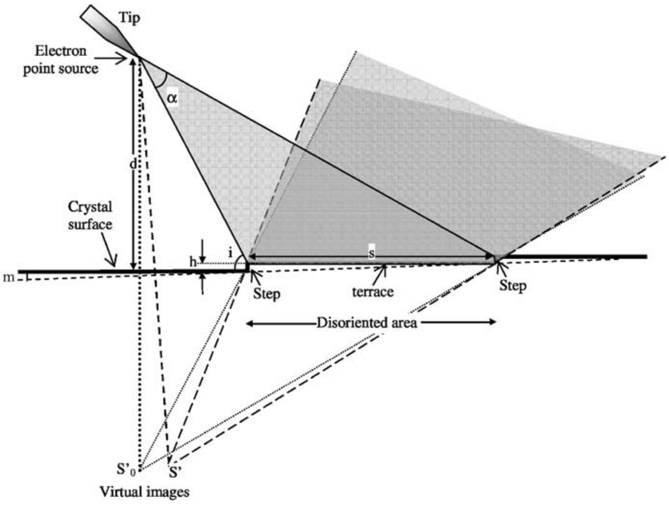

Fig. 2. Reflection from a stepped surface. A disoriented area is a succession of equal width s terraces limited by equal height h steps. This provides overlaps in the reflected images from different part of the surface.

2. Experimental

Our approach to provide such a short distance shielding is in the use of a coaxial structure which integrates the field emission tip. This structure, described in a previous study [8] is made of a sharp etched W tip positioned inside a glass capillary. A metal layer deposited on the outer wall of the capillary constitutes an electrical sheath. The total diameter of the structure can be made as small as 60 μm. By applying a negative voltage between 60 and 200 V to the tip relative to the sheath, nA electron currents can be extracted from the tip. Using this structure as the source of a transmission projection microscope, we showed that the sheath shields the electrostatic influence of a third conductor placed