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Enhancement of SEM to scanning LEEM

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Abstract

By introducing a cathode lens below or inside the objective lens of a scanning electron microscope, many experiments similar to those typical of the LEEM method can be performed. The conditions for the diffraction of slow electrons are modified by the convergence of the primary beam, and challenges include the necessity of managing the signal species propagating along the optical axis in a direction opposite to that of the primary beam. However, even a simple implementation, providing the integral dark-field signal only, has not only delivered plenty of results in the very low energy range below 50 eV, but the performance in the range of hundreds of eV and units of keV has also been substantially improved. The scanning LEEM method is illustrated using experimental results acquired by additionally employing multichannel detection and detection of transmitted electrons.

Keywords: Scanning low-energy electron microscopy; Electron emission; Low-energy electron diffraction; Surface electronic phenomena; SEM

1. Introduction

Over the last two decades the low energy electron microscope (LEEM) has established itself as a powerful tool for studying solid surfaces [1,2]. The key optical element is the cathode lens (CL), which is an immersion electrostatic lens in which the sample serves as its cathode. The homogeneous component of the cathode lens field retards the incident wave to the desired low energy. A planar electron wave is created by focusing the primary beam into the back focal plane of the objective lens. Similarly to TEM/STEM complementarity, a scanning version of LEEM is attracting attention.

The scanning electron microscope (SEM) is widely used for the observation of bulk specimens. During its entire history, the advantage of using a low-energy electron beam has been acknowledged, and many attempts have been made to implement it [3]. Nowadays, SEMs offer a resolution of 4 nm at 100 eV landing energy. However, both calculations and experience have shown the CL principle to be the only way to overcome this energy limit. We have been dealing with this solution both theoretically and experimentally, and have introduced the CL into a commercial SEM and collected a large amount of convincing experimental results [4]. Because of the common CL principle, we call the method scanning LEEM (SLEEM). The aim of this paper is to summarize our recent results of electron optics and detection systems, and to present newly acquired contrasts. In particular, the role of the angular aperture of the primary beam will be discussed. The formation of contrasts in three types of detectors will be presented with application examples.

2. Electron optics in SLEEM

Long ago, the CL aberration disc size was shown to be proportional to the ratio of the initial energy of the emitted electron to its final energy after acceleration [5]. This means the lower the electron energy in the sample plane, the better the resolution – a property contrary to that preventing the users of standard SEMs from lowering the beam energy arbitrarily. Thus, the SLEEM mode profits from the correction of aberrations of the focusing objective lens [6,7].

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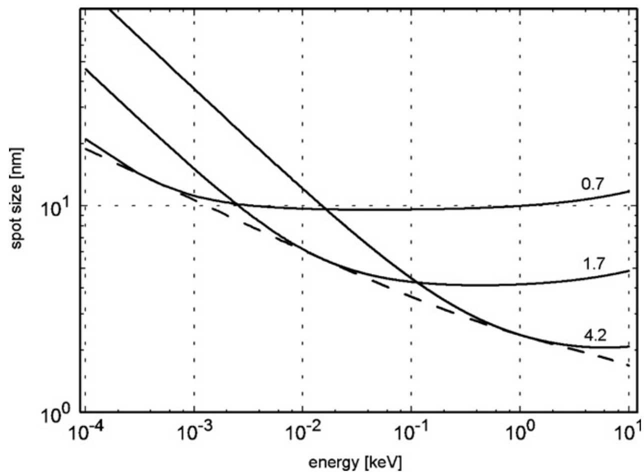

Fig. 1. Ultimate spot size calculated for the optimum aperture (dashed line) and the spot sizes obtained for three fixed angular apertures of the beam in a plane between the objective and cathode lenses, labeled in mrad (solid lines). The other parameters are aberration coefficients of the focusing lens $C_S = C_C = 10$ mm, beam current 20 pA, gun brightness 10^8 A cm^{-2} sr^{-1}, primary energy 10 keV, and energy spread 0.5 eV.

The spot sizes in Fig. 1 were calculated by applying the summation rule based on defined encircled currents [8], while the aberration coefficients of the magnetic focusing closed-field objective lens and the CL were calculated using analytical equations [6]. Experimentally, 9 nm has been presented as a 25/75 edge resolution at 10 eV (with a primary energy of 10 keV) on an Au/C testing specimen with a top-class SEM adapted to the SLEEM mode [9]. In Fig. 1, we see that achieving the ultimate spot size below 1 eV requires the beam aperture to be reduced significantly, though still much less than what would be needed in a conventional SEM.

In the SLEEM, the primary beam spot is focused onto the object plane of the objective/CL assembly, conjugate to the sample surface. The CL includes an electrostatic field penetrating the anode bore, which acts, in both LEEM and SLEEM instruments, as a diverging lens. The homogeneous part of the field in the LEEM only decelerates the incident planar wave. However, in the convergent probe of the SLEEM, the axial velocities are lowered with respect to the radial velocities, so that the angular aperture of the probe enlarges. In Fig. 2, we see that if the image resolution is to be kept near the ultimate resolution, final beam apertures in the sample plane must be 20–100 mrad. Under these conditions, analogous to convergent beam electron diffraction (CBED) in the STEM, the diffracted beams can easily overlap, thereby enhancing the total dark-field signal intensity.

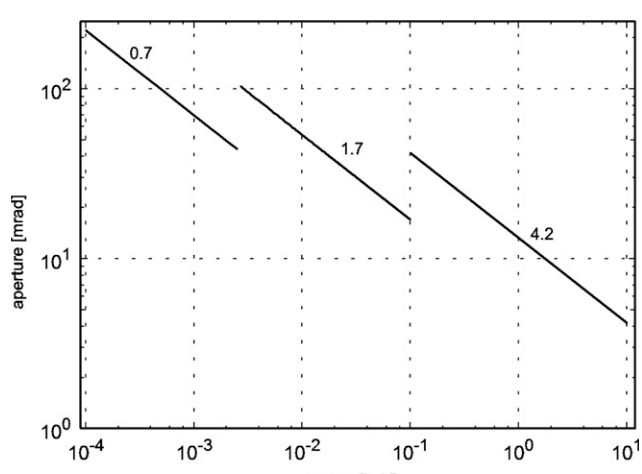

Fig. 2. Energy dependence of the beam aperture in the specimen plane for three fixed beam apertures between the focusing and cathode lenses shown in Fig. 1.

3. Detectors

3.1. Detector of reflected electrons

Our most often used adaptation of an SEM to the SLEEM mode is outlined in Fig. 3. The cathode lens is inserted below the focusing objective lens in the form of an anode/detector electrode, while the insulated specimen serves as the cathode biased to a negative potential that is finely and fluently adjustable from 0 up to a limit exceeding the accelerating voltage of the SEM, usually 15 kV. The detector is formed of a single-crystal scintillator disc, usually with outer/inner diameters of 10/0.3 mm [4,7]. This simplest implementation is suitable for an academic style adaptation of a commercial SEM, and substantially improves the image resolution at low beam energies to near the nominal guaranteed resolution. The long working distance (of about 8 mm) and loss of the axial part of the signal beam (see [10]) are drawbacks. Advantages include the observability of fluent changes in the contrast formation from, for example, 15 keV (BSE mode) to 1 eV (SLEEM mode), with moderate corrections in focusing and magnification, which are accomplishable using analytical relations [11].

3.2. Detector of transmitted electrons

The inelastic mean free path (IMFP) of an electron in a solid generally shortens with decreasing energy, but in-

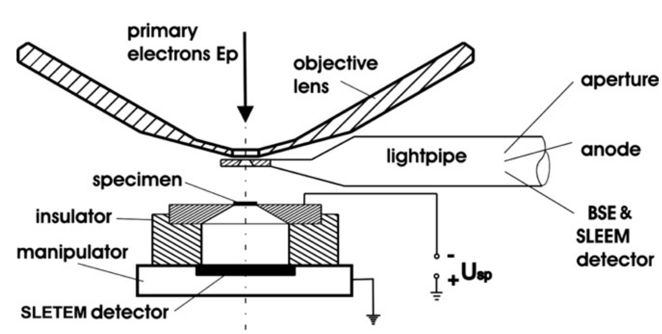

Fig. 3. Scheme of the experimental setup of an SEM equipped with the CL assembly and also containing detectors of reflected and transmitted slow electrons.