Ultramicroscopy 130 (2013) 13–28

Contents lists available at SciVerse ScienceDirect

Ultramicroscopy

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

A monochromatic, aberration-corrected, dual-beam low energy electron microscope

Marian Mankos*, Khashayar Shadman

Electron Optica Inc., 1000 Elwell Court #110, Palo Alto, CA 94303, United States

ARTICLE INFO

Available online 21 March 2013

Keywords:
Low energy electron microscopy
Monochromator
Aberration correction
Dual beam illumination
DNA sequencing
Contrast

ABSTRACT

The monochromatic, aberration-corrected, dual-beam low energy electron microscope (MAD-LEEM) is a novel instrument aimed at imaging of nanostructures and surfaces at sub-nanometer resolution that includes a monochromator, aberration corrector and dual beam illumination. The monochromator reduces the energy spread of the illuminating electron beam, which significantly improves spectroscopic and spatial resolution. The aberration corrector utilizes an electron mirror with negative aberrations that can be used to compensate the aberrations of the LEEM objective lens for a range of electron energies. Dual flood illumination eliminates charging generated when a conventional LEEM is used to image insulating specimens. MAD-LEEM is designed for the purpose of imaging biological and insulating specimens, which are difficult to image with conventional LEEM, Low-Voltage SEM, and TEM instruments. The MAD-LEEM instrument can also be used as a general purpose LEEM with significantly improved resolution. The low impact energy of the electrons is critical for avoiding beam damage, as high energy electrons with keV kinetic energies used in SEMs and TEMs cause irreversible change to many specimens, in particular biological materials. A potential application for MAD-LEEM is in DNA sequencing, which demands imaging techniques that enable DNA sequencing at high resolution and speed, and at low cost. The key advantages of the MAD-LEEM approach for this application are the low electron impact energies, the long read lengths, and the absence of heavy-atom DNA labeling. Image contrast simulations of the detectability of individual nucleotides in a DNA strand have been developed in order to refine the optics blur and DNA base contrast requirements for this application.

1. Introduction

Low energy electron microscopy is a technique for imaging electrons that are reflected by the specimen. The technique was developed in the 1980s by professor E. Bauer's group [1]. In Fig. 1, a schematic diagram of a LEEM is shown. The illuminating electrons are emitted from the surface of a cathode, accelerated to their final beam energy, typically 10–25 keV, and focused into a beam separator. The beam separator, a magnetic prism array, bends the electron beam towards the axis of the objective lens. The immersion objective lens decelerates the electrons to a landing energy ranging from 0 eV to a few 100 eV and illuminates the substrate surface with a broad beam. In the opposite direction, moving away from the substrate, the objective lens simultaneously accelerates the reflected and emitted electrons and magnifies the image. As the electrons reenter the beam separator, they are deflected into the projection optics, which further magnifies the image on a scintillating screen. The image formed on the screen is then viewed by a CCD camera and saved on a computer. The extremely low energy of the illuminating electrons makes LEEM an exquisitely sensitive surface imaging technique, capable of imaging single atomic layers with high contrast [2]. Furthermore, the low electron impact energies prevent radiation damage to sensitive samples such as biological molecules. The main drawbacks of LEEM are its susceptibility to chromatic aberrations and charging effects. In spite of the short deBroglie wavelength, which is in the range of Angstroms, the lateral resolution of conventional LEEM instruments is limited to a few nm. In addition, when a conventional LEEM is used to image insulating specimens, sample charging adversely impacts the low energy electron beam, and blurs and distorts the image.

MAD-LEEM is a novel instrument that aims to overcome the aforementioned drawbacks associated with present-day LEEM. The instrument utilizes an energy filtering mechanism to reduce the energy spread of the electron beam to 25 meV or less. It also employs electron mirrors as aberration correcting elements to achieve sub-nm resolution over a relatively large field of view. Last, it illuminates the sample with a second overlapping electron beam with a different landing energy to neutralize the charge deposited by the imaging beam, thereby eliminating surface charging.

* Corresponding author.
E-mail address: marian@electronoptica.com (M. Mankos).

0304-3991/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ultramic.2013.02.018

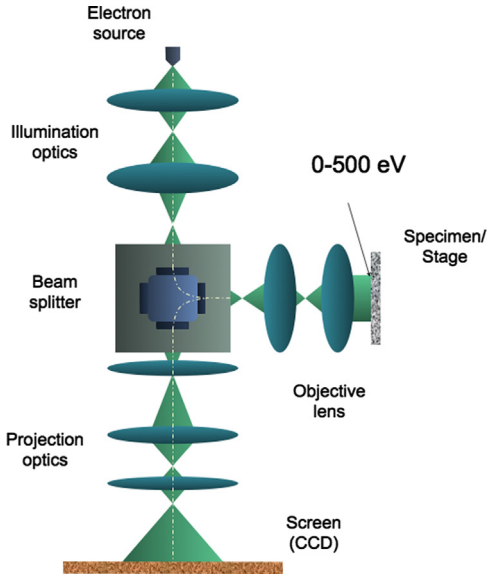

Fig. 1. Schematic layout of a LEEM column.

2. Electron-optical column

A schematic layout of the MAD-LEEM electron-optical column, shown in Fig. 2 represents the conceptual design of the MAD-LEEM column and shows the critical electron-optical elements needed to illustrate the imaging principles. Many of the elements typically present in a detailed column design, e.g transfer and field lenses, alignment and stigmation coils, etc. are omitted here for clarity. The column contains two independent illumination beams, a monochromator, and an aberration corrector which are combined into a single column by beam separators. The beam separators are based on compact, double-focusing magnetic prism arrays composed of uniform magnetic fields of different strength and length. Each separator quadrant deflects the beam by 90 degrees and transfers stigmatically two planes, the diffraction (slit) and (achromatic) image plane, with unit magnification. The excitations of the coils are chosen so that the prism behaves as a thick, round field lens along the curved axis and bends the beam by 90 degrees. The aberration contribution of the individual beam separators is typically minimized by placing a highly-magnified image at the achromatic plane at the center of this field lens. The two illumination beams are for imaging the sample and for mitigating sample charging. The imaging beam optics includes a monochromator that reduces the electron energy spread to 25 meV or less. The main beam separator deflects both beams towards the objective lens, where the electrons are decelerated and focused to form parallel flood beams. The electrons are back-scattered by the specimen, reaccelerated, and focused by the objective lens to form an aberrated image. The lower beam separator transports the image formed by the back-scattered electrons first into a symmetry mirror that compensates for the separator energy dispersion and then into a mirror aberration corrector (MAC) that corrects the spherical and chromatic aberrations of the objective lens. The specimen image is transferred from the center of the beam separator into the object/image plane of the MAC. The MAC images the specimen image onto itself, without forming an intermediate image in the MAC. A field lens placed at the object/image plane of the MAC is used to focus the diffraction/slit plane and control the field rays. The MAC is then set to cancel the combined aberrations of the objective lens and any intermediate transfer and field lenses. Electrons reflected by the aberration corrector are then transported back through the beam separators into the projection optics, which magnifies the image on a viewing screen. In general, a highly magnified image of the sample surface is placed at the center achromatic plane of the beam separators, while the diffraction pattern is placed at the energy-dispersed separator slit plane. On the illumination side, the source image is transferred via the beam separator slit planes into the objective lens back-focal plane, while its angular distribution is transferred via beam separator achromatic planes and used to illuminate the specimen. The justifications for the new features provided by this instrument are described in more detail below.

2.1. Monochromator

Commonly used electron sources such as thermionic emitters (W, LaB_6) or thermally assisted (Schottky) field emitters produce an electron beam with an energy spread in the range of 0.5 eV–2 eV. In order to obtain detailed information about the chemical composition, interatomic bonding, and local electronic states of macromolecules, an energy resolution of 0.2 eV or less is necessary [3]. Thus, a monochromator is needed to reduce the energy spread of the illuminating beam [4,5]. We have developed a novel monochromator [6] utilizing a beam separator, an electron mirror and a knife edge aperture, as shown in Fig. 3. This novel monochromator design also has the potential to further improve the spatial resolution of a LEEM, as it reduces the higher order chromatic aberrations, thereby easing the task for the aberration corrector. In addition, the monochromator together with an electron gun can be used as a stand-alone unit [7] to provide a source of monochromatic electrons that can be utilized to significantly improve spatial resolution in Low-Voltage SEM (LVSEM) and improve energy resolution and spectroscopy in energy-filtered TEM.

The electron source, biased at a high negative voltage, emits electrons with an energy spread, ΔE. The beam passes through the beam separator, which deflects the beam into the electron mirror. The electrons with nominal beam energy E_0 are deflected by 90 degrees (solid, green lines), while electrons with a slightly lower energy (dashed red lines) or higher energy (dotted, purple lines) are deflected slightly more or less, respectively, as a result of the energy dispersion of the beam separator. The axial bundle of rays with energies in the range ($E_0-\Delta E$, $E_0+\Delta E$) appears to emanate from a point near the center plane of the beam separator, also known as the achromatic point (plane). The virtual source image is focused at the plane of a knife edge-shaped aperture in order to achieve high energy resolution. As the electrons proceed towards the electron mirror, a knife edge-shaped aperture stops a fraction of the electrons, in this case the electrons with slightly higher energies, $E_0+\Delta E$, as shown in Fig. 3. The transfer lens focuses the achromatic point at the reflection plane of the electron mirror, which reflects all the electrons back into the beam separator and images the virtual source back at the knife edge plane. As the remaining electrons proceed back to the beam separator, the lower energy electrons with energies $E_0-\Delta E$ are stopped by the same knife edge-shaped aperture. This arrangement allows the use of a simple knife edge as the energy selecting device, which is a much simpler and more reliable design when compared to the narrow, often sub-micrometer slits needed in typical monochromator designs. The remaining electrons have a reduced energy spread, which can be adjusted by the knife edge position. These electrons reenter the beam separator and are deflected a second time by 90 degrees onto the axis of the electron source. After the double pass through the beam separator and the electron mirror, the dispersion introduced by the monochromator vanishes due to symmetry, which is desirable for high resolution imaging. Without the second pass through the beam separator, the beam would acquire energy dispersion, which is detrimental for high resolution imaging in the remaining optics as cross-term aberrations between the