Nuclear Instruments and Methods in Physics Research A 645 (2011) 60–67

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Electron optics of multi-beam scanning electron microscope

A. Mohammadi-Gheidari *, P. Kruit

Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands

ARTICLE INFO

Available online 21 December 2010

Keywords:
Electron optics
Multi-beam scanning electron microscope
MBSEM
High throughput
High resolution

ABSTRACT

We have developed a multi-beam scanning electron microscope (MBSEM), which delivers a square array of 196 focused beams onto a sample with a resolution and current per beam comparable to a state of the art single beam SEM. It consists of a commercially available FEI Nova-nano 200 SEM column equipped with a novel multi-electron beam source module. The key challenge in the electron optical design of the MBSEM is to minimize the off-axial aberrations of the lenses. This article addresses the electron optical design of the system and presents the result of optics simulations for a specific setting of the system. It is shown that it is possible to design a system with a theoretical axial spot size of 1.2 nm at 15 kV with a probe current of 26 pA. The off-axial aberrations for the outermost beam add up 0.8 nm, increasing the probe size to 1.5 nm.

1. Introduction

Charged particle lithography and microscopy instruments are key tools in science and industry. Scanning electron microscopes can reach resolutions below 1 nm. The acquisition time for noise-free high resolution images of 10^6 pixels is typically in the order of seconds. When used for patterning, the writing time for 10^6 pixels is in the same order of magnitude. For some applications, both in patterning and in imaging, this is too slow. However, current in a single beam cannot easily be increased without degrading the resolution due to the limited reduced brightness of the electron source. Multi-beam systems can enhance the throughput by several orders of magnitude. Many approaches have been tried to make multi-electron beam systems over the last decades [1–11]. There are basically two major challenges for multi-beam systems: to find an appropriate electron source, and to focus multiple beams onto the sample. In the single column/single source approach [7–12], which we will adopt, multiple beams are created by splitting the wide angle beam of a single source into many sub-beams, forming an intermediate focus using a micro-fabricated lens array. A single column with common cross-overs of all beams is then used to focus the beams on the sample. For splitting up a single source, two kinds of sources have been used so far: LaB_6 sources and dispenser type cathodes [12]. Both emitters provide a very high current but for high resolution applications the brightness is too low.

We have developed a multi-beam scanning electron microscope (MBSEM) as a tool for fast and high resolution patterning through the electron beam induced deposition (EBID), with a resolution down to 1 nm, similar to a state of the art single beam SEM. This system is currently able to deliver 196 focused beams onto the sample [13]. The instrument may also be used for high throughput ordinary resist-based electron beam lithography, and for fast imaging (the latter, of course, only after a suitable detector has been developed).

To develop a high resolution MBSEM, we have used a commercially available column of a Nova nano 200 SEM (FEI Company) and designed a novel multi-beam source module that splits the beam of a high brightness Schottky source. A consequence of using a single column system to image the multiple beams is that electron beams have to travel off-axis through the SEM lenses. The key challenge in the electron optical design of the MBSEM is to minimize the off-axial aberrations of the lenses. The objective of this article is to describe the electron optical design of the MBSEM and show the simulation results of the off-axial aberrations.

2. General design considerations for a multi-beam SEM

The design principle of the multi-beam source for our system has been described in detail elsewhere [14]. We shall summarize some specific details here, which are necessary to appreciate the challenges of designing the optical system of the MBSEM.

Fig. 1 shows a schematic drawing of the multi-beam source (MBS) used in the MBSEM to produce an array of focused beams. In the MBS the emission cone of a high brightness Schottky emitter is split into an array of focused beams by an aperture lens array. The lens array consists of a thin Si membrane with apertures of 18 μm diameter at a 25 μm pitch. Two macro electrodes in combination with the extractor electrode of the electron source and the aperture plate create a so called "zero-strength macro lens". "Zero strength"

* Corresponding author. Tel.: +31152788161.
E-mail address: A.M.Gheidari@tudelft.nl (A. Mohammadi-Gheidari).

0168-9002/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2010.12.090

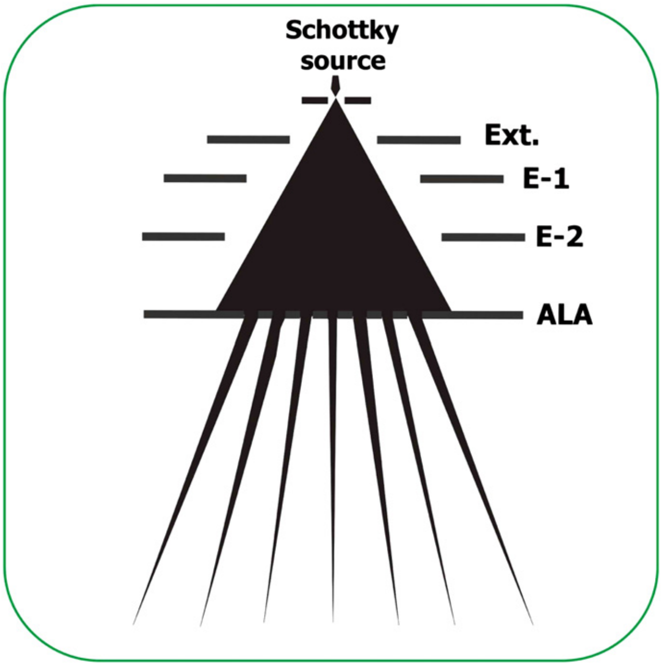

Fig. 1. Schematic drawing of the multi-beam source (MBS) used in the MBSEM to produce an array of focused beams.

means that the off-axis beams are not deflected, thus avoiding the problem associated with chromatic deflection errors. The field from the macro electrodes ends on the aperture plate, forming low aberration single aperture lenses for the micro-beams.

By manipulating the shape of the field at the aperture plate, field curvature can be corrected, so the array of micro-beams focuses in a flat plane. Using a single aperture lens array also avoids any precise alignment of two or more electrodes which is the case, for instance, in a micro-Einzel lens array [11]. Thus, assuming a Schottky source with a reduced brightness of 5×10^{7} A/m^2 sr V, a virtual source size of 30 nm and an angular current density at 5 kV extractor voltage of 0.24 mA/sr, the output of the source unit is an array of 14×14 beams with a total current of 157 nA, at an acceleration energy of 1.5 kV, focused to a geometrical spot of approximately 95 nm, at a pitch of 70 μm, where the outer beam has an angle of 32 mrad with respect to the axis.

It is possible to design and build a system with individual micro-columns for each beam. However, it is not easy to align all optical elements with respect to each other and direct the beams through each column. For high resolution applications, where the total beam current is relatively low, we can afford to have common cross-overs of the beams without deterioration of the beam quality as a result of electron–electron interactions. Thus, we choose to use a single column for transporting the output of the multi-beam source to the target.

When all 196 beams are focused by single lenses, it is obvious that most beams travel off-axially through the column. The off-axis aberrations of the lenses may then degrade the resolution of the system. Therefore the key challenge is now to minimize the off-axis contributions of the lenses. The simplest solution is to only place lenses where all beams have a common cross-over, because at those points none of the beams is off-axis. However, then we need lenses to image one common cross-over to the next cross-over. If these "field lenses" are placed in the planes where the sub-beams are focused, that are in conjugate planes of the source and the sample, the off-axis aberrations cannot (in the thin-lens approximation) influence the resolution. The disadvantages of this solution are the large number of lenses that are needed and the rigidity of the system: once built, the magnification or probe size cannot be changed anymore.

We have chosen a design in which only the last lens, the objective lens, is situated at a common cross-over, and only the first lens after the multi-beam source is a field lens. The reason for the first decision is that, just as in a conventional single beam SEM, the last lens of the MBSEM demagnifies all aberration contributions of other lenses, so its own aberrations are dominant. The reason for the second decision is that we expect that we can keep the off-axial distance of the beams smaller in the rest of the column than in this output plane of the source. In addition, this is the lens that needs to collimate the diverging beams from the source. From fairly simple first order estimates, one can find that chromatic deflection errors alone would be larger than the geometric size of the source image if this lens is not in a conjugate plane of the source.

3. First-order optical system design

With the design principles set out in the previous paragraph, we can attempt to use a standard SEM. We had an FEI Nova nano 200 SEM available, so to get a better understanding of the electron optical challenges involved in the design of a MBSEM let us look briefly at the electron optics column of the standard single beam SEM. Fig. 2 shows a schematic drawing of electron optical configuration. In this system the single beam produced by a Schottky source is imaged by subsequent lenses to form a probe. The "gun lens" (C1) and the C2 lens make an intermediate image of the Schottky virtual source in front of the variable aperture (VA). The

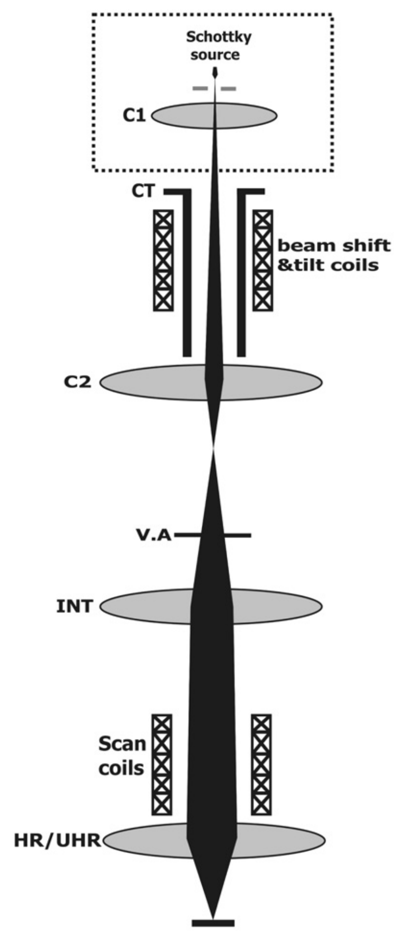

Fig. 2. Schematic overview of electron optical configuration of the standard Nova nano 200 SEM.