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Electron optics of multi-beam scanning electron microscope

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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.

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. Ho

[8], [9], [10], [11], [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.

Section snippets

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…

First-order optical system design

Accelerator lens design

The design of the accelerator lens needs some special attention. We mentioned that, because it is used as a field lens, its aberrations would not influence the resolution if it may be considered a thin lens. However it should possess an acceptable spherical aberration coefficient for the imaging of the first common crossover. This is because the spherical aberration causes a spread in the position of the different beams in the common cross-over, making the cross-over not so "common" anymore....

Optics simulations of axial performance (method)

The axial probe size, d_{axial}, containing 50% of the total current, is calculated using the RPS algorithm proposed by Barth and Kruit [17]. It should be noted that the FW50 measure for the probe size calculation will be used throughout this paper unless otherwise mentioned. $d_{axial} = \left\{ \left[d_I^{1.3} + (d_\lambda^4 + d_S^4)^{1.3/4} \right]^{2/1.3} + d_C^2 \right\}^{1/2}$ here d_I, d_λ, d_S and d_C are the FW50 contributions to the probe size of source image, diffraction, spherical aberration and chromatic aberration, respectively, with the following...

Optics simulations of axial performance (results)

Fig. 6 shows a more detailed schematic overview of the MBSEM imaging sequence. Sections A to F (A–F) show the procedure of imaging of the array of Schottky virtual sources and sections G to I show the imaging of the common cross-overs (G–I). For example section "A" comprises the zero strength lens where "S" is the position of the Schottky virtual source and "e" is the image position of the zero strength lens (which should be the same for a perfect zero strength). The 14×14 array of source...

Optics simulations of off-axial performance (method)

In the MBSEM beams are traveling off-axially to the lenses. Therefore, for the probe size quantification of each beam, it is required to include the off-axial aberration contributions to the axial probe size. This is done by calculating the off-axis aberration contribution of each lens (sections A, B, C, D, E and F) at the sample and adding them to the axial spot size.

opening angle is chosen to give the smallest probe possible for this setting. Fig. 12 shows the off-axial contributions to the outer probe of all subsequent lenses. The off-axial contribution of the last lens of the system is the smallest contribution. This is due to the fact that the common crossover of the beams is in the coma free plane of the lens. Thus, the off-axial contributions of the INT lens...

Conclusion

We have demonstrated, by detailed computer simulation of the full optical system, that it is possible to mount a multi-beam source on a standard scanning electron microscope and form multiple focused beams in the sample plane with the same beam size and beam current that was obtainable in the original SEM. The design of a low aberration coupling lens between the multi-beam source and the SEM is critical. For the suppression of off-axial aberrations, the first image plane of the source, with...

Acknowledgment

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References (19)

Yanxia Zhang *et al.*
Phys. Procedia. (2008)

T. Chang *et al.*
Microelectron. Eng. (2001)

B. Roelofs *et al.*
Microelectron. Eng. (1984)

M. McCord
J. Vac. Sci. Technol. B (1997)

E. Yin *et al.*
J. Vac. Sci. Technol. B (2000)

S. Tanimoto *et al.*
Jpn. J. Appl. Phys. (2003)

J. Vac. Sci. Technol. B (2000)

There are more references available in the full text version of this article.

Cited by (17)

Large scale three-dimensional reconstruction of an entire Caenorhabditis elegans larva using AutoCUTS-SEM

2017, Journal of Structural Biology

> *Citation Excerpt :*
>
> ...The advantages of AutoCUTS-SEM could be further expanded when the speed of SEM image acquisition is improved, to allow a large amount of information obtained in a shorter period of time. A new SEM instrument with multi beams to enable parallel, high speed and large-field image acquisition (Kasthuri et al., 2015; Marx, 2013) (Mohammadi-Gheidari and Kruit, 2011) could be one solution to increase the speed. Segmentation of data is currently the “bottleneck” in larger-volume 3D reconstruction (Briggman and Bock, 2012; Peddie and Collinson, 2014)....

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A high-current scanning electron microscope with multi-beam optics

2016, Microelectronic Engineering

> *Citation Excerpt :*
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> ...However, the current in a single beam system, and thus the throughput, is limited by the available brightness of the electron source and the limited aperture angle due to the aberrations of the objective lens. In order to overcome this limitation, a multi-beam SEM has been developed to deliver 196 beams to a specimen [1–4]. Such a microscope also needs 196 separate detectors which is not trivial task....

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Multi-electron-beam deflector array

2014, Microelectronic Engineering

> *Citation Excerpt :*
>
> ...Typical aperture diameters are 5–100 μm at a pitch of 20–250 μm. In contrast with the design and fabrication of macroscopic deflectors, micro-fabricated deflector design and fabrication is relatively new in the electron optics community [3–17]. One of the biggest challenges for multi-beam deflectors is to minimize the number of control wires necessary to control all these deflectors....

...The system uses 61 beams for parallel acquisition in a hexagonal array across multiple detectors, with the potential to generate phenomenal quantities of data at high speed. Similarly, a multibeam SEM instrument has been reported that employs 196 'beamlets' in a 14 × 14 array to achieve a minimum probe size of ~1 nm (Mohammadi-Gheidari et al., 2010; Mohammadi-Gheidari and Kruit, 2011). Furthermore, a multi-energy deconvolution imaging strategy has been developed, which can record high resolution isotropic datasets by combining sequential image acquisition over increasing electron beam landing energies (and therefore increasing interaction volumes), with deconvolution methods to enhance depth information (FEI Company; Lich et al., 2013)....

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A large current scanning electron microscope with MEMS-based multi-beam optics

2014, Microelectronic Engineering

Citation Excerpt :

...The only effect of the macrolens aberration is to shift the beamlet in the second microlens array, but the microlens will still focus all electrons in the same point on the sample [1]. Recently a multi-beam scanning electron microscope (MBSEM) has been developed, which delivers 196 focused beams (array of 14 × 14), each of which has around 1 nA [2–5]. Of course this is a more complicated system than sketched in Fig. 1, but it is also more flexible and gives a good experimental platform to try the new idea....

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2018, Journal of Physics D: Applied Physics

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Ultramicroscopy, Volume 146, 2014, pp. 27-32

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