Real-time Diagnostic Tools for the Scanning Electron Microscope

Liuchuyao Xu
Robinson College

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Contents

1 Introduction

1.1 Project Objectives

The scanning electron microscope (SEM) is a type of microscope that produces images using signals generated from the interaction between electrons and the surface under observation. Higher resolution can be achieved compared to the traditional optical microscope, since electrons have much lower wavelength than light. An SEM can have resolution lower than one nanometre, whereas that of an optical microscope is often limited to a few hundred nanometres [4]. This has benefited a variety of fields. For example, scientists have been using the SEM to analyse the doping density in semiconductor [2]. The goal of the project is to develop software tools in Python to support diagnosis of SEM images for the purpose of assisting the operator or automating procedures.

1.2 Theory of the SEM

Figure 1 shows the basic construction of an SEM. The electron gun generates an electron beam, which is transformed into an electron probe after passing through the condenser lens and objective lens. It is scanned across the specimen under the effect of the scanning coil. As a result of the interaction between the incident electrons and the specimen, some electrons are emitted from the specimen. These are called secondary electrons and are collected by the detector, which generates signals whose magnitude depend on the strength of the secondary electrons. The display unit produces one frame after each complete scan of the specimen.

1.3 How Fast Computing Can Aid SEM Operators

The quality of an SEM image is affected by aberrations. While some exist because of the fundamental properties of the microscope and are difficult to get rid of, some can be completely eliminated by adjusting relevant settings. Two important ones are focus and stigmation, which directly affect the resolution and astigmatism of the image, respectively. Figure 3 illustrates the effect of wrong focus and stigmation settings.

Focus determines the focal point of the electron probe. When the focal point is far from the surface of the specimen, the incident electrons interact with the specimen in a larger area. As a result, spots near each other produce signals of closer magnitude. This makes the image appear blurry, as shown in Figure 3b.

Stigmation controls stigmators in the SEM, which are used to compensate for astigmatism. Astigmatism arises due to imperfections in components of the SEM, and describes uneven focus in the electron probe, as shown in Figure 2. When the electron probe is out of focus, astigmatism makes the incident electrons interact with the specimen in an elliptical area, and thus makes the image appear stretched. When the electron probe is in focus, astigmatism makes the image appear blurry. Figure 4 gives some examples of distorted images.

Although experienced SEM operators can often find the right settings for focus and stigmation in a short time, it may not be as straightforward for new users. Sometimes, the surface being observed may have a complex structure and makes adjusting even harder. The complexity arises because any judgement of an image is based on what the operators see through their eyes, which is rather subjective. Intensive training and practical experience are often required for an operator to become efficient in using the SEM.

Fast computing can aid the operators in a few ways. Firstly, a numerical evaluation of the quality of the image may be provided, which eliminates the subjectivity in using human eyes. Numbers are also easier to note down if any record is required. Two operators may have different views on the same image, but the numbers will not be different. Therefore, cooperation and communication between operators can be enhanced. The use of numbers also enable automatic procedures for adjusting settings of the SEM, which save time and may produce better results than doing it manually.

The project focuses on developing tools that use Fast Fourier Transform (FFT) to help operators evaluate the focusing and astigmatism of SEM images, and also looks into an algorithm for the automatic correction of them.

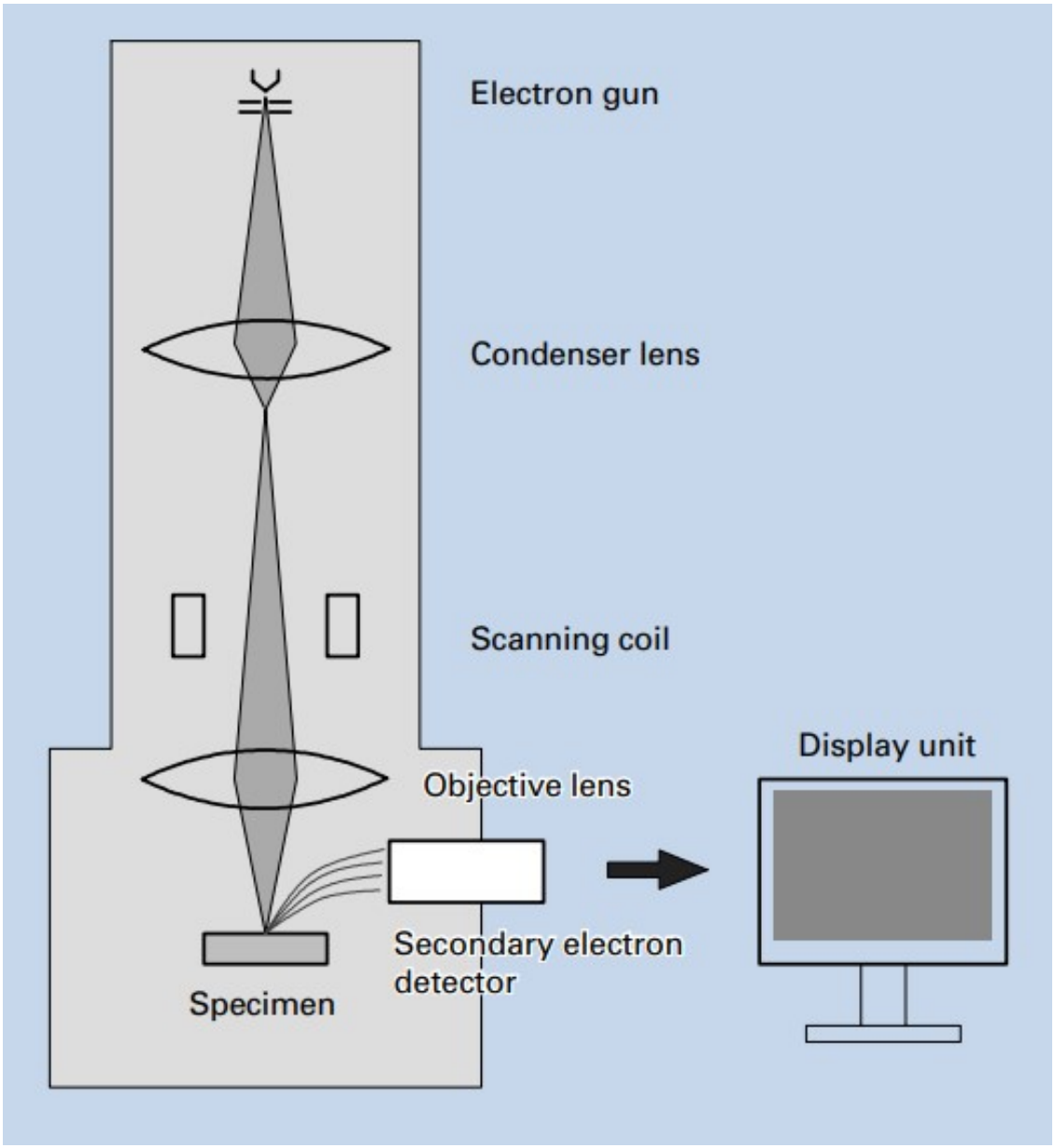


Figure 1: Basic construction of an SEM [1]

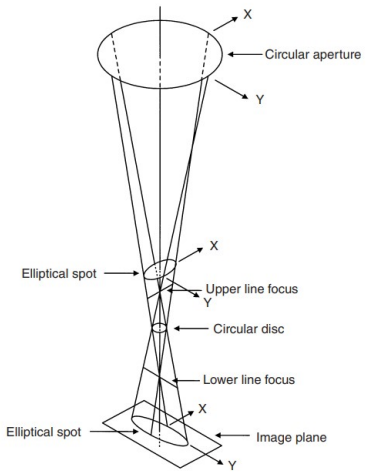
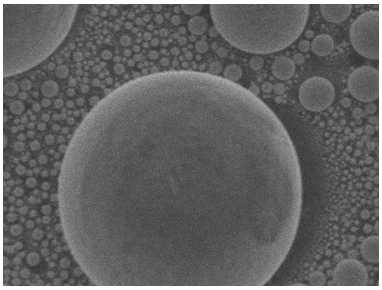
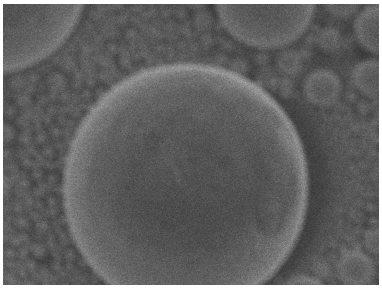


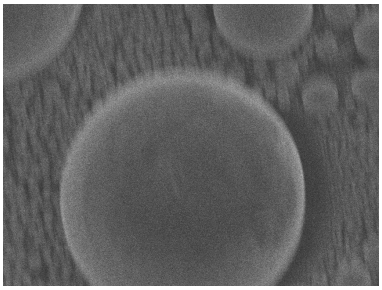
Figure 2: Uneven focus of the SEM



(a) In focus

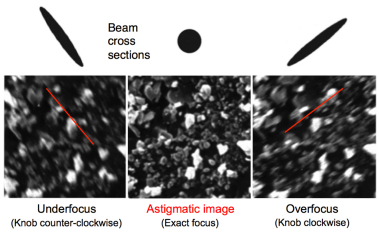


(b) Out of focus

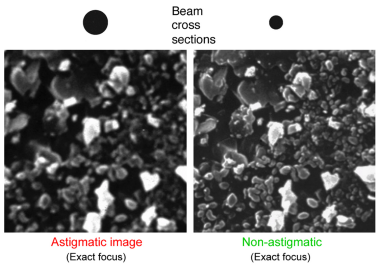


(c) In focus with astigmatism

Figure 3: Sample SEM images



(a) Astigmatic images



(b) Astigmatic and non-astigmatic image

Figure 4: Sample astigmatic SEM images [6]

2 The Algorithms

2.1 Histogram Equalisation

There are many types of histograms in image processing. The grey level (brightness level) pixel intensity histogram, which plots the number of pixels of each grey value in the image, is the most relevant one for SEM images. This is because an SEM translates the energy of the secondary electrons directly into a grey level, colours do not exist in SEM images.

The algorithm for obtaining the histogram of an SEM image is given by

$$n_l = \frac{1}{P} \sum_p I(l_p = l) \tag{1}$$

where n_l is the normalised number of pixels of grey level l, P is the total number of pixels in the image and l_p is the grey level of the p_{th} pixel.

Figure 5a shows an 8-bit grey-scale image, i.e. its depth of digitisation is 8-bit and it has 256 grey levels. Figure 5b shows the histogram of the image and its integral. As can be seen in the histogram, most pixels are concentrated in the middle of the grey scale. This is reflected by the fact that the image is missing its highlights and shadows.

Histogram equalisation is a method for adjusting the distribution of pixel intensities of an image, in order to improve its overall contrast. Effectively, it is achieved by spreading out the more frequent intensity values. To perform histogram equalisation, first obtain the integral of the histogram using

$$s_l = \sum_{i=1}^{l} n_i$$

where s_l is the value of the integral at grey level l. The integral spans from 0 to 1 as the histogram is normalised. Scale the integral by the maximum grey level and preform rounding to create the transform function

$$f_l = \lfloor s_l L \rfloor \tag{2}$$

If a pixel in the original image has grey level l, it will have grey level f_l in the transformed image. For example, if all pixels in the original image are concentrated between grey level 100 to 200, the pixels of level 100 will become 0 in the new image while the pixels of level 200 will become 255 (assuming 8-bit image).

The result is more noticeable when the image has a low contrast, such as the one shown in Figure 5a. The histogram-equalised version of it is given in Figure 5c and the new histogram in Figure 5d. More details are now visible as the contrast has been enhanced.

2.2 Fast Fourier Transform

Idea of FT. Maths of FFT.

2.3 Focusing and Astigmatism Correction

Idea. Algorithm and flow chart.

3 The Software

3.1 Overview

Overview of all modules.

3.2 The SemImage Module

Idea of the module. Classes and functions. Demo code. Possible improvements.

3.3 The SemTool Module

Idea of the module. Classes and functions. Demo code. Possible improvements.

3.4 The SemCorrector Module

Idea of the module. Classes and functions. Demo code. Possible improvements.

4 Demonstrations

4.1 Real-time Histogram Equalisation

Screenshots of the software. Demonstration of the algorithm. Speed test of the algorithm.

4.2 Real-time Fast Fourier Transform

Screenshots of the software. Demonstration of the algorithm. Speed test of the algorithm.

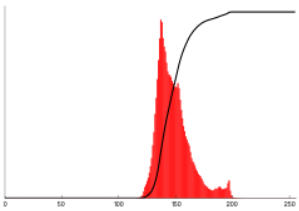
4.3 Automatic Focusing and Astigmatism Correction

Screenshots of the software. Demonstration of the algorithm. Speed test of the algorithm.

5 Next Steps

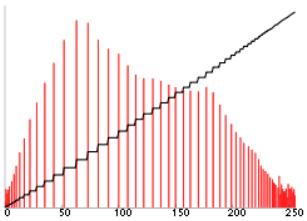
Next steps.

(a) Original image



(b) Histogram of original image

(c) Histogram-equalised image



(d) Histogram of histogram-equalised image

Figure 5: Histogram and histogram equalisation [5]

References

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[2] T. Agemura and T. Sekiguchi, "Secondary electron spectroscopy for imaging semiconductor materials," 2018 International Symposium on Semiconductor Manufacturing (ISSM), Tokyo, Japan, 2018, pp. 1-3, doi: 10.1109/ISSM.2018.8651171.

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[6] "Correcting Astigmatism in SEM Images." cambridge.org. https://www.cambridge.org/core/journals/microscopy-today/article/correcting-astigmatism-in-sem-images/7ED43987C7916AAFBE1869522546AC84/core-reader (accessed May 10, 2020).