SEM Image Distortion Measurement Based on Silver Nanowires

G N Yao, D Zhao* and M Qiu
State Key Laboratory of Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University, Hangzhou, 310027, China
E-mail: zhaoding@zju.edu.cn

Abstract. In scanning electron microscopy, electromagnetic distortion is one of the main causes of pattern distortion. This distortion typically manifests as periodic vibration at high frequency scanning speeds. The article establishes a model for describing the pattern distortion when the edge of the sample is inconsistent with the scanning direction. As the basis for distortion solutions.

1. Introduction

As a high-resolution imaging tool, scanning electron microscope (SEM) has been widely used in observation of material morphology. However, its image resolution would be significantly affected by electromagnetic interference including magnetic field interference and electric field distortion. Pluska et al. believe that the effect of electric field distortion on the position of the electron beam is independent of the working distance, which is the distance between the final aperture of SEM column and the sample surface. There is a significant difference in the distribution of the magnetic field within the SEM chamber and within the column. It is assumed that the electric and magnetic fields within the cavity are uniform within a certain range. The influence of the magnetic field in the cavity on the horizontal displacement of the electron beam is linear with the square of the working distance, while the displacement of the electron beam caused by the magnetic field in the column and the working distance is linear. And it is possible to calculate the intensity of two magnetic fields separately by observing the images inside the SEM at different distances [3, [4].

Image distortions induced by electromagnetic interference are usually visible in SEM, where irregular zigzag patterns can be observed at high magnification scanning. When the scanning direction along the x-axis is perpendicular to the direction of the edge of the sample, and the dwell time between two adjacent SEM scanning lines is much shorter than the vibration period, the distortion of the pattern
can be considered as the component of the actual distortion direction in the x-axis direction (Figure 1). In this paper, The smooth edges of silver nanowires are used to observe vibration. The distortion components in x and y directions were obtained by mathematical solutions under the condition that the scan direction can be arbitrary. This method can reduce the error caused by the scan direction and provide reference for the further improvement of image quality by electromagnetic shielding [2] or digital image correlation [1,5,6].

![Figure 1](image.png)

**Figure 1.** (a) SEM scan direction is set to be horizontal (x-axis) and the scanned nanowires are perpendicular to the scan direction. (b) The amplitude $A$ of this image is the horizontal component of the actual distortion.

**2. Experiments and calculations**

The SEM images are taken by ZEISS Sigma. About 5 uL of silver nanowire suspension was dripped onto the surface of silicon substrate. After the water evaporates completely, the sample is placed under SEM. As shown in Figure 2, the observed distortions are different according to various view angles of nanowires. The frequency $f$ of vibration can be calculated by the following formula:

$$f = \frac{H}{ht}$$  \hspace{1cm} (1)

where $H$ and $h$ are the height of the whole image and the height of a single vibration peak, respectively, and $t$ is the scanning time of an image.

We measured 30 groups of data. Affected by measurement precision and random error, the measured vibration frequency ranges from 45 Hz to 53 Hz. Considering that the AC signal frequency of the driving electron gun is 50 Hz, the measured results are in good agreement with it.
Figure 2 (a)-(c) nanowire patterns observed by SEM (magnification of 500K, electron gun voltage of 20 KV, working distance of 9.1 mm), while (d) measures the vibration amplitude of 10 sets of nanowires with different tilt angles. It can be seen that the distortion amplitude increases with the angle.

The edges of the scanned pattern can be described by equations. The horizontal and vertical directions of the image are the x-axis and the y-axis. The nanowire can be seen as a straight line with a slope of k (Equation 2). Distortion is periodic; the relationship between the distortion in x and y directions and time can be approximated by equation 3 and 4. $a_0$, $b_0$ are components of the distortion along the scanning direction and the vertical scanning direction, respectively. In the experiments, the scanning direction is always in the horizontal direction, so $a_0$, $b_0$ can be considered as distortion components along the x-axis and y-axis directions. Since the period of the line scan is much smaller than the period of vibration, Therefore, it can be considered that the pattern period is equal to the actual period. $\omega$ is the vibration frequency. The scan direction of the SEM is shown in Figure 1(b), and the scan function can be approximated by the equation (5), where $H$ is the height of the entire image and $v$ is the scanning speed of the image from top to bottom:

\[ y' = kx' \]  \hfill (2)  
\[ x = a_0 \sin \omega t + x' \]  \hfill (3)  
\[ y = b_0 \sin \omega t + y' \]  \hfill (4)  
\[ y = H - vt \]  \hfill (5)  

The simultaneous equations (1) - (4) can be obtained by:

\[ kx = y - (ka_0 + b_0) \sin \left( \omega \frac{H-y}{v} \right) \]  \hfill (6)
In order to calculate the amplitude, the following conditions need to be satisfied:

\[(\omega \frac{H-y_1}{v}) = 2n\pi \]  \hspace{1cm} (7)

\[(\omega \frac{H-y_2}{v}) = 2n\pi + \frac{\pi}{2} \]  \hspace{1cm} (8)

Let \( \Delta y = y_2 - y_1 \), then we have:

\[\Delta y = \frac{\pi v}{2\omega} \]  \hspace{1cm} (9)

\[k\Delta x = \Delta y + (ka_0 + b_0) \]  \hspace{1cm} (10)

The value of \( \Delta x \) is the distortion value \( A \) measured on the image:

\[A = \Delta x = a_0 + \frac{\pi v + b_0}{2ka_0} \]  \hspace{1cm} (11)

Equation (11) shows the relationship between the pattern vibration amplitude and the actual vibration amplitude. The trajectory of the electron is shifted by the magnetic force of Lorentz in the magnetic field, the magnitude of the distortion is related to two factors: one is the moving distance of the electron in the magnetic field (working distance), and the other is the energy of the electron. For observations with constant electron energy and working distance, the distortion value can be considered as fixed. The scanning direction is usually set to the horizontal direction. When the nanowire direction is perpendicular to the scanning direction, in this case, \( k \) is considered close to infinity. And amplitude \( A \) is equal to \( a_0 \). When the angle between the nanowire and the vertical direction increases, the vibration amplitude of the scan pattern also increases. This experimental result is in line with expectations (Figure 2b-d).

3. Results and conclusions

In order to illustrate the relationship between the distortion value \( A \) and the slope of the nanowire edge \( k \), the peak-to-peak values of the distortion of the nanowires at different angles were measured under the same conditions, where the nanowire angle refers to the angle between the nanowire and the vertical direction (y-axis). Figure 3(a) and (b) reflect the linear relationship between \( A \) and the reciprocal of \( k \). The difference between Figure 3(a) and (b) is that the working distance of the electron beam is changed, and the actual distortion amplitude \( D \) satisfies the following equation:

\[D = (a_0^2 + b_0^2)^{\frac{1}{2}} \]  \hspace{1cm} (12)
Figure 3 Analyze 15 groups of observation data under the same conditions with linear fitting. (a) and (b) correspond to different working distances $d_1 = 8.3\, \text{mm}$, $d_2 = 9.1\, \text{mm}$.

The experimental results are calculated as follows:

\begin{equation}
A_{d=8.3\, \text{mm}} = 6.15 \frac{1}{k} + 3.992 
\end{equation}

\begin{equation}
D_{d=8.3\, \text{mm}} = (a_0^2 + b_0^2) \frac{1}{k} = 3.1718 \, \text{nm} 
\end{equation}

\begin{equation}
A_{d=9.1\, \text{mm}} = 3.246 \frac{1}{k} + 2.562 
\end{equation}

\begin{equation}
D_{d=9.1\, \text{mm}} = (a_0^2 + b_0^2) \frac{1}{k} = 3.6759 \, \text{nm} 
\end{equation}

It can be seen that the direction of distortion changes at different working distances, and the distortion amplitude will decrease with working distance.

In summary, the article describes a measure of the SEM’s internal pattern distortion. Besides, a mathematical model was established to describe the relationship between the size of the distortion and the angle between the edge of the sample and the direction of the scan. A series of data was measured to prove this relationship, which provides a data reference for distorted solutions, especially software solutions.
Reference

[1] Burglin T R 2000 *J. Microsc.* **200** 75–80
[2] Ishiba T, Suzuki H 1974 *Jap. J. Appl. Phys.* **13** 457–62
[3] Płuska M, Czerwinski A, Ratajczak J, Katecki J, Rak, R 2006 *J. Microsc.* **224** 89-92
[4] Płuska M, Czerwinski A, Ratajczak J, Katecki J, Oskwarek L, Rak R 2008 *Micron* **40** 46-50
[5] P JIN, X LI 2015 *J. Microsc.* **260** 268–280
[6] Spagnoli C, Beyder A, Besch S R, Sachs F 2007 *Rev. Sci. Instrum.* **78** 36111-1–36111-3
[7] Xu L, Tian X, Li X, Shang G, Yao J 2011 *Meas. Sci. Technol.* **22** 114023-1–114023-9