Chromatic and Spherical Aberration Correction in the LSI Inspection Scanning Electron Microscope

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This paper describes the principle and an experimental result of the chromatic and spherical aberration correction in the scanning electron microscope (SEM) based on the aberration correction method which Zach et al. have developed with a multipole corrector [1][2]. The equipped corrector has been newly developed and designed to suit to the JWS-7555S(JEOL) column, which has been used for the LSI inspection in semiconductor manufacturing. In this use of the SEM, lower acceleration voltage, below 1 keV, has been routinely used nowadays for observing the LSI specimen to minimize the damage from the electron beam collision and the specimen charging-up. In addition to that, the largely-tilted SEM image such as 60 degrees is required to observe boundary microstructures. The objective lens must be conical and has a longer working distance, which increases the aberration coefficients. The aberration correction can be expected to overcome these difficulties.

We have attained a corrected resolution below 2.5 nm at 1 keV acceleration voltage with the newly installed aberration corrector.

Introduction

So far the dominant aberrations, which deteriorate the SEM image, have been the 1st-order chromatic and 3rd-order spherical aberrations of the objective lens. Consequently column engineers have been struggling to “reduce” these aberrations because Scherzer proved theoretically in 1936 that the chromatic and the spherical aberration coefficients are always positive with the rotationally symmetric lens. The aberration reduction technique has been developed such as the magnetic field immersion objective lens, the static electric retarding field objective lens and the compound one of these fields. However, these objective lenses have limitations of the resolution as well as of observing conditions. As for the latter, these are useful only for horizontal images. On the contrary, there are several proposals to “vanish” these aberrations by canceling those positive aberrations with generating negative ones by adapting another non-rotationally symmetric multipole lenses [3]. However sophisticated matters with the multipole have revealed the difficulties against constructing a mechanically-precise and systematically-stable correction system for several tens of years. Zach et al. have overcome these difficulties by using 12-pole-pin multipole computer control system, which can compensate the miss-alignment factor and the residual aberration by composing several multipole fields, di-, quadr-, hexa-, octo-pole fields [1][2].

In the region of the semiconductor manufacturing, the aberration correction is suited well to the LSI inspection, which has to be made with a lower acceleration voltage such as below 1 keV. In order to show the practicality and the efficiency of the aberration correction experimentally, we have developed and constructed a suitable correction system to the JWS-7555S(JEOL), the LSI inspection scanning electron microscope.

Principles of the Chromatic and Spherical Aberration Correction

The principles of the chromatic and spherical aberration correction, which we have employed, are based on the Zach’s method [1][2]. In this section, short explanations for some key points of his correction principles are summarized.

Chromatic aberration correction

The 1st-order chromatic aberration in each X- and Y-direction can be compensated independently by using four quadru-pole elements. The electron beam paths, X- and Y-trajectory, in the corrector are shown in the following figure.
Here, \( m_o, m_s \) and \( m_t \) mean the magnifications of the objective lens, of the total X- and Y-direction quadru-pole lenses on the specimen. Comparing the \( f_x \) and \( f_y \) in eqs. (1)-(4), \( Q_2 \) part in \( f_x \), is half of that in \( f_y \), which means that it is possible to vary \( C_{xv} \) and \( C_{yv} \) independently and arbitrarily with keeping the electron trajectories to certain paths. If the stigmatic trajectory condition is kept as in Fig.1 passing through the center of \( Q_{2;2} \) and \( P_{2;2} \), in the \( Y \)-direction and of \( Q_{2;3} \) and \( P_{2;3} \) in the \( X \)-direction, \( C_{xv} \) and \( C_{yv} \) are controlled only to be compensated by changing the combination ratio \( Q_{2;2} \) and \( P_{2;2} \). The total chromatic aberration is corrected by adjusting the 2nd- and 3rd-stage quadru-pole fields to satisfy the condition in \( C_{xv} \), where \( C_{xv} \) means the chromatic aberration coefficient of the objective lens.

\[
C_{xv} = C_{yv} - C_{wv} \tag{5}
\]

### Spherical aberration correction

In the ordinal round lens, because of the rotationally symmetric field, the spherical aberration has only to be concerned with the 3rd-order aperture aberration in one direction. In the non-rotationally symmetric lens, however, composed 3rd-order aperture aberrations in the \( X \)-and \( Y \)-directions appear explicitly. The 3rd-order aperture aberrations in the \( X \)-and \( Y \)-direction, \( \Delta x \) and \( \Delta y \), with the corrector and the objective lens are written as eqs. (6) and (7).

\[
\Delta x = (C_{30} x_i^3 + C_{12} x_i y_i^2 + C_{21} x_i^2 y_i^2 + C_{20} y_i^2) \tag{6a}
\]

\[
\Delta y = (C_{03} y_i^3 + C_{21} y_i x_i^2 + C_{20} y_i x_i^2 + C_{12} y_i^2 x_i^2) \tag{7a}
\]

Strictly speaking, in the stigmatic condition, the following conditions written in eq. (9) are to be fulfilled.

\[
C_{30} + C_{03} + C_{12} + C_{21} = 0 \tag{8a}
\]

\[
C_{03} + C_{21} = 0 \tag{8b}
\]

Then the condition (8d) turns out to be of no use. The cross-term aberration coefficient \( C_{i-j} \), which is fixed after the chromatic aberration correction being completed, is compensated by the outer octo-pole fields in the condition (8c). Then \( C_{03} \), \( C_{30} \), \( C_{21} \) and \( C_{12} \) are negligible on the same reason as the chromatic aberration correction. Consequently the 3rd-order aperture aberration correction condition turns out to be the conditions (8a-d).

### Experimental

#### System configuration

A schematic diagram of the experimental aberration correction system is shown in Fig. 2. The corrector is installed in the JWS-7555S(JEOL) scanning electron microscope, which consists of the TFE (thermal field emitter), the probe current control lenses (CL1, CL2), the intermediate acceleration lens (Vint) and the compound lenses (CL1, CL2), the intermediate acceleration lens (Vint) and the compound lenses (CL1, CL2), the intermediate acceleration lens (Vint) and the compound
magnetic and retarding fields) objective lens (OL). The corrector is inserted between the OL aperture and the intermediate acceleration lens in order to maintain the proper dynamic range of the corrector driver unit. Because the column potential is the GND level and the energy potential below the intermediate acceleration is boosted in 8 keV and finally it returns to the original level by the retarding field, setting the corrector driver unit to the lower potential produces better dynamic range compared with setting it to the higher potential. A schematic diagram of the corrector is shown in Fig. 3. The corrector consists of 4 stages of 12-pole-pin multipole. In the 2nd- and 3rd-stage multipole especially, coils are wound around poles to generate the quadrupole magnetic field. The correction control software is installed into the host computer, which enables the easy operation of the complicated 12-pole-pin and 4-stage multipole system using the graphical user interface (GUI). The electric and the magnetic potential \( V(t,p) \) are assigned to each pole as in Fig. 4 using trigonometric functions, where \( Gx \) and \( Gy \) mean the gain to be controlled. Each multipole field is loaded simultaneously based on the linear summation theorem.

A calculated electron beam path is shown in Fig. 5. In order to maintain the stable condition of the corrector, the cross-over position of the inlet side to the corrector is fixed to the optimum which brings the optimum aperture angle at approximately 16 mrad on the image plane. In the outlet side from the corrector, the beam path goes through near the center of the intermediate acceleration lens (Vint) so as not to be bent largely by its strong field. The objective lens has such a conical shape as to tilt the specimen up to 60 degrees. So the WD (working distance) is 4 mm and the \( C_s = 7.5 \) mm, \( C_c = 3.6 \) mm at 1keV on the original specification of this column (without correction) that limits the resolution to 5 nm at the same acceleration voltage. If the 1st-order chromatic and the 3rd-order spherical aberrations are completely compensated by the corrector on this column, the theoretical resolution limit is estimated of 1.5 nm at 1keV.

**Adjustment of the multipole fields of the corrector**

The practical adjustment method is also the same as the Zach's method, which is described in his article in detail [1][2]. In the following, main points are briefly summarized.

**Correction flow**

The correction has to be made in sequence and iteration. The correction flow is shown in Fig. 6. Before the “correction start”, the electron beam has to be aligned without corrector. Firstly the theoretical correction values are set to the correction control unit, which is very important because the system is so complicated as to lose the SEM image if the values are not properly chosen. Secondly the stigmatic trajectory, which is mentioned previously, has to be completed absolutely. If the line-images in the 2nd- and 3rd-stage are mis-aligned, severe residual aberrations are generated. After that, \( C_c \) and \( C_s \) correction procedures are followed. Finally the residual aberrations, coma, 45-degree, 3-fold and 4-fold astigmatisms etc. are compensated. Generally the \( C_c \) and the residual aberration corrections have to be made iteratively because the 3rd-order aperture aberration system is linked together.

**\( C_c \) correction**

The focusing error \( \Delta f \), which is induced by the chromatic aberration, can be written in the power series of the beam energy divergence \( \kappa = \Delta E / E \) as shown in eq. (10), where \( E \) denotes the electron beam energy.

\[
\Delta f = \kappa C_c + \kappa^2 K_c + \ldots \tag{10}
\]

Here, \( C_c \) and \( K_c \) are the 1st-order and the 2nd-order chromatic aberration coefficients respectively. Higher order aberrations are...
negligible in this case because only $C_c$ can be compensated. The graphical representation of eq. (10) is shown in Fig. 7. Generally the TFE has the energy spread $|\Delta E| = 0.5$ to 0.8 eV, which broadens the focusing position by $|\Delta f_c| (\text{un-corrected})$ as shown in the figure. If the $C_c$ vanishes, only the quadratic term remains in eq. (10), which means $|\Delta f_c| (\text{corrected})$ becomes negligibly small. In order to make this condition visible, the energy of the electron beam is slightly shifted up and down, that is $E_2$ and $E_1$ respectively. If the system is corrected, the image planes of those energies are on the same position, $\Delta f(E_1) = \Delta f(E_2)$. When observing a round shape particle, by searching $\Delta f$ which makes the 1-dimensional edge clear at both $E_1$ and $E_2$ as shown in Fig. 8, it is possible to detect the corrected condition.

$C_s$ correction

The spherical aberration makes the caustic surface of the electron beam as shown in Fig. 9, which shows the case of the under correction, that is $C_s > 0$. The intensity profile of the source side electron beam has two peaks in such a case. And these peaks appear on the...
opposite side of the image plane in the case of the over correction, that is \( C_i < 0 \). These two peaks make a double focused SEM image and the correction condition can be adjusted so as not to appear the double image in both sides, that is \( C_i = 0 \).

The 3rd-order aperture aberration has not only the isotropic spherical aberration but also the four-fold astigmatism, which are generated in accordance with the composing ratio of \( C_{ij}^{\text{quad}} \) and \( C_{ij}^{\text{astig}} \) in eqs. (8a-d). A schematic image of the four-fold astigmatism is shown in Fig. 10. It resembles four leaves, which spread to ±45-degrees direction. \( P_{4,i} \) means the octo-pole field of the i-th stage. After the four-fold astigmatism is compensated by the outer octo-pole fields \( P_{4,1} \) and \( P_{4,4} \), the spherical aberration must be re-compensated by the inner octo-pole fields \( P_{4,2} \) and \( P_{4,3} \) iteratively because they are linked together.

**Corrected SEM image**

An original SEM image (without corrector) and a corrected SEM image (with corrector) of gold particles on carbon substrate are illustrated in **Fig. 11** and **Fig. 12** respectively with 1 keV acceleration voltage and 30 pA probe current. When these two images are compared, the superior image quality and higher resolution are easily observed in the corrected image. The resolution of the corrected image is approximately 2.5 nm. A tilted image in 45 degrees is shown in **Fig. 13**, which shows 0.5 μm Line & Space resist patterns at 1 keV acceleration voltage. Microstructures on the side-wall of the patterns are clearly visible.

**Conclusion**

The applied column of the corrector has a long working distance (4 mm) and a conical shape objective lens (60 degrees), which increases the aberration. However the resolution could be reduced to 2.5 nm (corrected) dramatically and stably from 5 nm (un-corrected) at 1 keV acceleration voltage by the chromatic and spherical aberration correction. The present report demonstrates the usefulness and efficiency of the Zach’s correction method for such SEMs as those for the LSI inspection in the semiconductor industry.

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**Reference**