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Theoretical analysis of scanning electron microscopes with plural detectors as an application field of photometric stereo

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ABSTRACT

Surface topography measurement methods using SEM with plural detectors are analyzed as an application field of photometric stereo. Plural-detector methods use images from several detectors. These images correspond to ordinary images made with the light source in different positions. SEMs are usually treated as a field for application of shape from shading, but we should consider that detector positions also affect the image intensities or shadings. Photometric stereo can therefore be applied to SEM - especially with plural detectors. This study shows experimental results and then gives some theoretical analyses needed to get high-resolution results. Exact rather than empirical formulas are given for calculating inclination angle from the data gathered by two- and four-detector SEM systems. An approach to eliminating the shadow distortion effect is shown.

INTRODUCTION

Products such as semiconductors and optical disks are becoming smaller and smaller with progress in microfabrication techniques. When these products are inspected in factories, scanning electron microscopes (SEMs) [1] are used to measure their dimensions. Not only 2-dimensional length measurements, but also 3-dimensional topography measurements have become important.

There are two kinds of methods using SEM to measure surface topography: specimen-stage-inclination methods, and plural detector methods. [2, 3, 4, 5] With specimen stage inclination, images are taken at different stage inclinations, (This is equivalent to the ordinary stereoscopic measurements). Plural-detector methods instead use images made by several detectors. As will be explained in the next section, these images correspond to ordinary images made with the light source in different positions, but with no geometrical changes caused by the different detector positions. In typical (two detector) plural-detectors methods, surface inclinations intersecting the axis between the two detectors are calculated by subtracting the intensities (or the square of the intensities) of each part of two images. [2, 3] One can obtain the sectional shapes of the specimens by adding these inclination values.

A lot of work in computer vision has been done on extracting surface normals from image intensities. Horn and his co-workers developed shape from shading, [6] which needs only one image to extract the normal distribution of the surface. These earlier works have considered that SEM image intensities depend only on the surface inclination, so they have treated SEM as an application field for shape from shading. Although this consideration is true under some limited conditions, it is usually a very crude approximation; we should therefore consider that detector positions also affect the image intensities or shadings. As will be shown in this paper, SEM - especially with plural detectors - is instead a possible application field for photometric stereo. [7, 8]

The next section presents these plural detector SEMs as applications of photometric stereo, and it shows experimental results for both reflection electron systems and secondary electron systems. For one of the specimens, both the two-detector method and the specimen-stage-inclination method are applied and their results are compared.

To get high-resolution results, we have to use secondary electrons and we need exact rather than experimental formulas for calculating surface inclination. To do this, we can model the SEM imaging process and analyze our plural-detector SEM theoretically. Then we can consider two of the main factors that give rise to distortion in the normal calculation. These factors are the coexistence of different materials on the surface, and presence of shadows made by local topographies. The final section of this paper shows how this shadow effect can be eliminated.

CORRESPONDENCE BETWEEN SEM AND THE ORDINARY OPTICAL SYSTEMS

First let us briefly review the SEM imaging process [1, 9] (**Fig. 1**). Electrons emitted from an electron gun pass through lenses and converge on the specimen as a narrow beam. Secondary electrons and reflection electrons exit from the specimen surface, and scans of the electron beam on the specimen are synchronized with the CRT scans. The numbers of electrons captured by the detector correspond to the intensity on the CRT. It is easy to see that changing the position of the detector does not affect the geometry of the observed image. It only affects the shading of the image. Thus the direction of the electron gun corresponds to the viewing direction and the direction of the detector corresponds to the direction of light sources. An electric field between the specimen and the detector is added in order to gather electrons. This is analogous to having light sources distribute around the detector position. When this electric field is strong enough, the light sources distribute in all directions. Then secondary electron images are said to be shadowless, as Horn and his co-workers assumed. Reflection electrons, however, have higher energies and their orbits are not affected by the

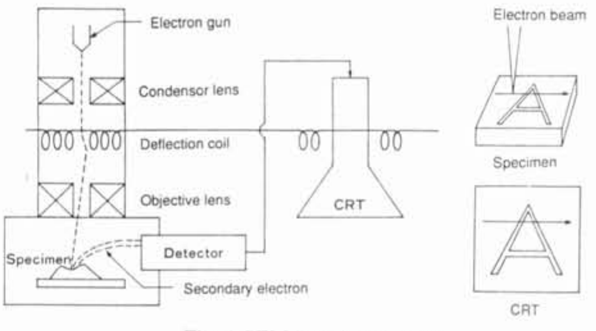
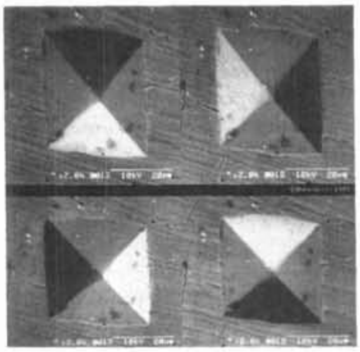
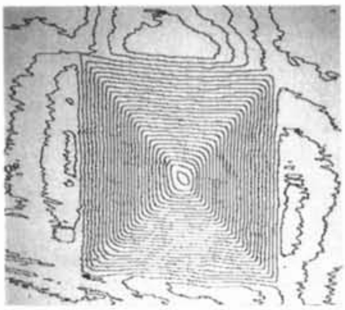


Fig. 1 SEM imaging process



(a) 4 detector image



(b) calculated contour

Fig. 2 Experimental result of Vicker's test

gathering electric field. Reflection electron images and secondary electron images made without a strong gathering electric filed are known to have clear detector position dependence.

EXPERIMENTAL RESULTS

In plural-detectors SEM, surface topography measurements are made as follows:

(1) image input

(2) calculation of surface normal distribution:

In most cases, simple subtraction of the signals from two detectors facing each other is used because it is roughly proportional to the surface inclination. Sato, [4] however, uses standard sphere sample image as a reference to decide the normal direction.

(3) calculating depth by summing the normal distribution

Two kinds of experimental results are shown here. One is from a system using four reflection electron to calculate detectors. Two detector pairs facing each other are used surface derivatives for two directions. **Figure 2** shows four images of a pyramid-like indent (Vicker's test), as well as the calculated contour.

The other experiment was done by rotating one secondary electron detector by 180°. In **Fig. 3**, a small scratch is seen and the surface profile is calculated. With the same sample, we made an experiment using the specimen-stage-inclination method using the 0° and 5° stage inclination images. It shows the same general features as the images made with the rotating detector (**Fig. 4**).

THEORETICAL EXTRACTION OF SURFACE NORMAL DISTRIBUTION FROM SEM

Model for secondary electron emission: In real situations, the intensity of SEM secondary electron images are decided not simply by the surface inclination and the detector position, but also by such factors, as the Edge effect, Material contrast, and Shadow by local topographies.

Reference 9 introduces a simple model for collection efficiencies, and this model is efficient for topographies whose typical dimension is on the order of 1 µm.

A. Conventional one-detector case

We assumed that:

(1) Secondary electrons are emitted from the specimen surface around the normal in accordance with the three-dimensional Lambert's law. (2) Emitted electrons near the specimen surface travel in a straight line. (3) All the electrons that hit the specimen surface after emission are absorbed. (4) All the electrons escaping from the specimen surface reach the detector. (5) Contributions of reentrant backscattered electrons are negligible.

Lambert's law says that the amount of secondary electrons emitted in the solid angle element dΩ of the departure angle q from the normal is proportional to cosqdΩ. We denote F as the proportion of electrons that can reach the detector:

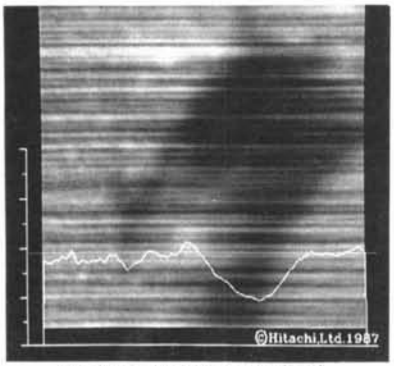
$$F = \frac{1}{\pi}\int_{\text{opening solid angle}} \cos q \, d\Omega \qquad (1)$$

B. SEM with plural detectors

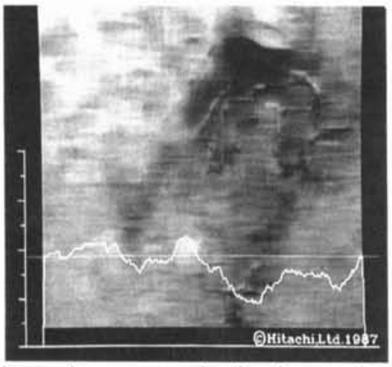
According to condition (4), we get shadowless images for open surfaces. But if we reconsider condition (4) for

(a) left detector image (b) right detector image (c) 3-d view

Fig. 3 Experimental result of a scratch



(a) two-detector method



(b) specimen-stage-inclination method

Fig. 4 Two-detector method and specimen-stage-inclination method

plural detector systems, a clear detector position dependence appears.

(4') All of the electrons escaping from the specimen surface reach the detector in the direction they were originally emitted.

For a system with two detectors, for example, one on the right and one on the left, secondary electrons emitted to the right reach the right detector and secondary electrons emitted to the left reach the left detector. Similarly, in a four-detector system (**Fig. 5**), secondary electrons emitted in each quadrant direction reach the corresponding detector. In these plural-detector systems, plural images having different detector positions (or different light source positions) can be obtained in a single scan of the specimen surface.

Ordinary SEMs have only one secondary electron detector, which can be replaced by a reflection electron detector. Annular-type reflection electron detectors can be attached to some SEMs. Most of the annular-type detectors are divided into four parts that can be used separately. Some SEMs have two secondary electron detectors, and, although it is not common, there are four-detector SEMs. Almost all SEMs have either one, two, or four detectors. In the next section, therefore, we will analyze only SEMs with two or four secondary electron detectors.

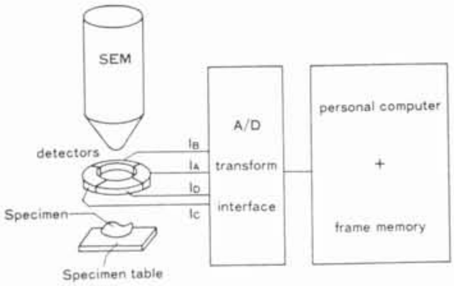


Fig. 5 Four detector SEM

Two secondary electron detectors: In a two-detector system, we can calculate the collection efficiency for each detector by integrating Eq. (1) over each solid angle. But according to the theorem in Ref. 9, within the weak electric field limit (the model stated above) we only have to integrate one dimensionally. For the shape shown in **Fig. 6**, collection efficiencies F_r and F_l of the right and left detectors, can be calculated as follows:

$$
\begin{aligned}
F_r &= \tfrac{1}{2}\left(\sin q_1 - \frac{h'}{\sqrt{1+h'^2}}\right)\\
F_l &= \tfrac{1}{2}\left(\sin q_2 + \frac{h'}{\sqrt{1+h'^2}}\right)
\end{aligned}
\qquad (2)
$$

For an open slope, q_1 and q_2 are equal to $\pi/2$. Then F_r and F_l become

$$
\begin{aligned}
F_r &= \tfrac{1}{2}\left(1 - \frac{h'}{\sqrt{1+h'^2}}\right)\\
F_l &= \tfrac{1}{2}\left(1 + \frac{h'}{\sqrt{1+h'^2}}\right)
\end{aligned}
\qquad (3)
$$

From these equations, we can solve for h' as follows:

$$h' = \frac{(F_r - F_l)}{2\sqrt{F_r F_l}} \qquad (4)$$

Because this equation is homogeneous in F_r and F_l, we can rewrite it with I_r and I_l, which are the right and left detector signals.

$$h' = \frac{(I_r - I_l)}{2\sqrt{I_r I_l}} \qquad (5)$$

If we locate the right detector in the positive direction of the X-axis, h' calculated above equals the x- derivative of the specimen surface. But Eqs. (4) and (5) do not hold when there are inclinations in the y direction.

Four secondary electron detector system: In four-detector systems, collection efficiencies are calculated by integrating Eq. (1) in each quadrant (**Fig. 5**). One of the detectors is located at a 45° angle between the x- and y- axis in each quadrant. Let us denote the normal vector by (-p, -q, 1) where p= $\partial z/\partial x$ and q= $\partial z/\partial y$. We can derive formulas to calculate p and q from the four detector signals I_A, I_B, I_C, and I_D.

$$
\begin{aligned}
p &= \frac{I_B + I_C - I_D - I_A}{\sqrt{3(I_B + I_C + I_D + I_A)^2 - 2\{(I_A + I_B)^2 + (I_B + I_C)^2 + (I_C + I_D)^2 + (I_D + I_A)^2\}}}\\
q &= \frac{I_C + I_D - I_A - I_B}{\sqrt{3(I_B + I_C + I_D + I_A)^2 - 2\{(I_A + I_B)^2 + (I_B + I_C)^2 + (I_C + I_D)^2 + (I_D + I_A)^2\}}}
\end{aligned}
\qquad (6)
$$

These are purely theoretical results, and the detailed proof is shown in Ref. 10.

DISTORTION FACTOR AND THEIR SOLUTION

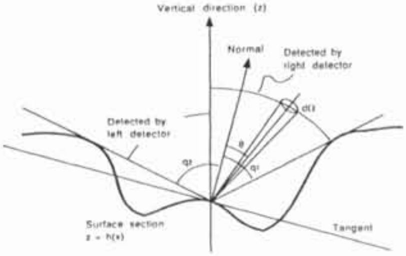
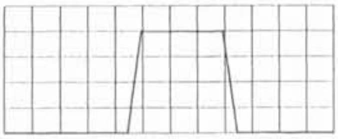
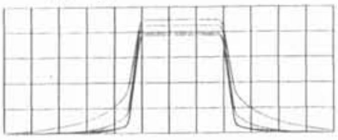


Fig. 6 Detection of secondary electron



(a) original model section



(b) calculated sections of first 5 iterations

Fig. 7 Correction of the shadow caused distortion

This section discusses two of the main factors: coexistence of different materials on the surface, and the shadow by the local topography. Then possible approaches for eliminating the shadow effect are shown.

Effect of coexistence of different materials: When the surface of the specimen consists of two or more materials, simple photometric methods that rely on the image intensities themselves fail because the number of the secondary electrons depends on the materials. This situation corresponds to the situation that occur in ordinary optical systems when the surface consists of materials that have different reflection properties.

But our formulas for the two-detector system and the four detector system each have a dimensionless form, which means that the image intensities are of the same order in the numerators and the denominators. In such dimensionless formulas, material factors are canceled. This means that in photometric measurement, it is not the image intensities themselves but the proportion of electrons distributed to each detector that decide the surface orientations. Thus if we use the look-up-table method, we should make a look-up-table using dimensionless quantities.

Effect of the shadow: Because photometric measurements directly relate image intensities and the surface inclination, they generally require that there be no shadow on the surface. In our model, conditions (4) or (4') ensure that no global shadow occurs, but local shadows are caused by the local topographies (condition 3). Using the secondary electron model proposed previously,[9] we can demonstrate the distortion in the blunted part of indented corners is caused by shadows (**Fig. 7**). Suganuma[2] attributed such bluntness to an effect of the local electric field. Quantitative analysis, however, shows that the local electric field cannot be strong enough to cause this distortion.

Correction of the shadow-caused distortion: This subsection proposes a distortion correction algorithm and shows the result of computer simulation for the two-detector SEM.

The following recursive algorithm is based on our collection efficiency model.[9]

(1) calculate the surface shape by using the detector signal.

(2) use the surface shape obtained on step 1 to calculate the shadow or collection efficiency

(3) use the shadow calculated in step 2 to estimate the shadowless signal

Repeating these three steps causes the surface shapes to converge to the original shape (**Fig. 7**). This algorithm can be applied only to the distributed light source system typical of SEM, and its recursive process is similar to the recent work on shape from interreflection.[10]

CONCLUSION

This analysis based on the theoretical model of secondary electron collection efficiencies can be summarized as follows.

(1) Plural detector SEM systems are an application field of photometric stereo.

(2) Formulas for calculating the surface inclination from the image intensities of each detector are deduced by using the weak electric field model of collection efficiency.

(3) Analysis of the distortion caused by shadows serves as the basis of an algorithm for correcting this distortion.

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