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Geometrical Electron Optics of the Shadow Image Distortion Method in a Transmission Electron Microscope

Katsuhiro Sasaki[1], Nobuyuki Tanaka[1], Hiroto Mori[1] Hidekazu Murata[2], Chiaki Morita[3], Hiroshi Shimoyama[2], Kotaro Kuroda[1]

[1] Department of Quantum Engineering, Nagoya University, Nagoya 464-8603, Japan
[2]Department of Electrical and Electronic Engineering Meijo University, Nagoya, Japan 468-8502
[3]EcoTopia Science Institute, Nagoya University, Nagoya, Japan 464-8603

The shadow image distortion (SID) method which we have bee developing is a simple and convenient method to observe electric and/or magnetic field in a conventional transmission electron microscopy. This method uses the effect of the deflection of electron beam due to the electric and/or magnetic field at the position of the specimen, and the deflection is detected as the distortion of the shadow image of the aperture which place at the position of the selected area diffraction (SAD) aperture. The detailed geometrical optics analysis and the determination of the optical parameters have been done in this work.

The holey carbon films (Quantifoil R2/2) with holes in a diameter of 2μm arranged in a square lattice pattern with a spacing of 4μm were placed both at the specimen and SAD aperture position and then the image and the shadow image of the films were observed, respectively. Both the images were recorded on to the same photographic film simultaneously, and the ratios of the magnification of the images were measured. Measurement has been done in a transmission electron microscope H-9000NAR at an accelerating voltage of 300kV.

In the previous work [1,2], we have found that the distortion (***D***) of the shadow image of the aperture is proportional to the field strength as to be $\boldsymbol{D = M_d M_{ap} aeEt / mv^2}$, where $\boldsymbol{M_d}$ and $\boldsymbol{M_{ap}}$ is determined by the strength of magnetic lens of the microscope, ***a*** is the distance between the specimen and the SAD aperture, and ***e***, ***m*** and ***v*** are the charge, mass and velocity of the electron in the microscope, respectively. The product of the field strength ***E*** and the thickness ***t*** where the field exists around the specimen can be determined by the distortion ***D***. The parameter $\boldsymbol{M_{ap}}$ which is determined by the objective lens can be unity if the objective lens current is turned off [1]. However, $\boldsymbol{M_d}$ which is determined by the condenser lens current can not be unity at any optical condition [2]. It has been confirmed that $\boldsymbol{M_d}$ can be measured as the magnification ratio between the image and the shadow image of the specimen and the SAD aperture on the florescent screen if the objective lens current is turned off.

Figure 1 shows that the simultaneously recorded image and shadow of the Quantifoil R2/2 which placed at the position of the specimen and the SAD aperture, respectively. The size and distance of the holes with exactly same size and shape were observed in different magnifications. The lay diagram of the microscope in this condition is shown in Fig. 2. The value of $\boldsymbol{M_d}$ can be determined as to be $\boldsymbol{1+a/c}$ [2], where ***c*** is the distance between the specimen and the focal point of electron beam by the condenser lens, as shown in Fig. 2. The distance ***a*** is the geometrically determined constant value to be 155 mm in our experiment. However, the value of ***c*** can be changed depending on the focal length $\boldsymbol{f_c}$ of condenser lens as to be $\boldsymbol{c = L_{c-o} - f_c}$, where $\boldsymbol{L_{c-o}}$ is the distance between the condenser and the objective lens The focal length of the condenser lens can be determined as to be $f_c = k_c/I_c^2$ [3] where k_c is the constant determined by the lens structure and I_c is the condenser lens current. Replacing c using L_{c-o} and k_c/I_c^2 gives

$$M_d = 1 + a/(L_{c-o} - k_c/I_c^2) \quad \text{------ (1)}$$

Rewriting this equation gives

$$a\, M_d/(1-M_d) = - k_c/I_{c2}^2 + L_{c-o} \quad \text{------(2)}$$

The result indicates that if the value of $a\, M_d/(1-M_d)$ is drawn as a function of $1/I_c^2$, a linear relation will be given, and then k_c and L_{c-o} can be given as the inverse ramp and the y-intercept of the linear relation, respectively. Figure 3 shows the $a\, M_d/(1-M_d)$ as a function of $1/I_c^2$ varying condenser lens current between 3.42 and 4.45 A while keeping other lens conditions in a constant. Apparently, the result shows a linear relation and gives the values of k_c and L_{c-o} to be 915 A^{2}mm and 218 mm, respectively.

In this work, it is proofed that the geometrical optics analysis can explain the optical condition of the SID method and the optical parameter M_d can be determined as a function of the condenser lens current.

References
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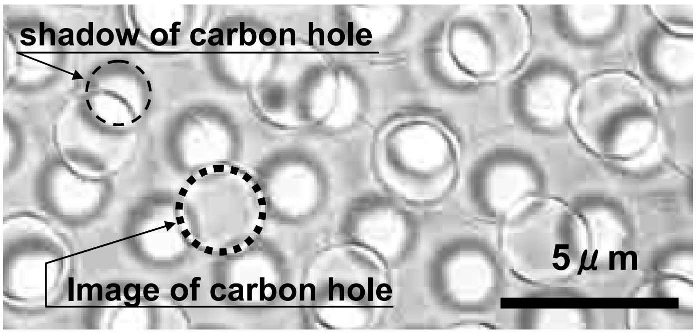

FIG. 1. Simultaneously recorded image and shadow image of Quantifoil 2/2

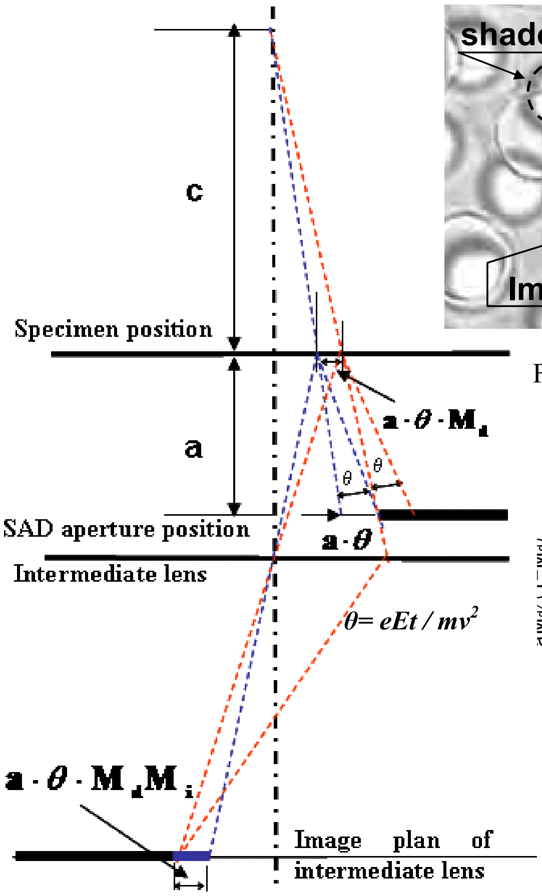

FIG. 2. The ray diagram of the electron optics of the SID method if the objective lens is turned off.

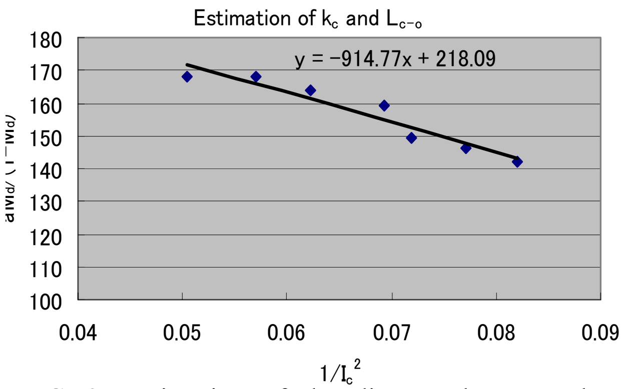

FIG. 3. Estimation of the distance between the condenser and the objective lens L_{c-o} and the lens constant of condenser lens k_c