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A simple method of the electric/magnetic field observation by a conventional transmission electron microscope

Katsuhiro Sasaki[a] and Hiroyasu Saka[b]

Department of Quantum Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Japan, 464-8603

[a]khsasaki@hix.nagoya-u.ac.jp, [b]Saka@numse.nagoya-u.ac.jp

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Abstract. A novel method to observe the electrostatic field distribution with a conventional transmission electron microscope has been developed. The method allows measurements of a potential difference less than 1V/μm. This method can be performed in any kind of conventional transmission electron microscope and applied to the observation of the electric/magnetic field at the level of a specimen.

Introduction

Two well known methods are often used to observe the electric/magnetic field distribution in a transmission electron microscope (TEM). The first one is electron holography [1], which requires a very expensive field-emission gun TEM (FEG-TEM). The other one is Lorenz microscopy. Though the latter method can be performed in a conventional TEM, the image in the Fresnel mode is obtained in defocused condition and, the image in the Foucault mode is not suitable for quantitative analysis [2].

During in-situ electron holography experiments [3], we found a distortion of the image of the selected area diffraction (SAD) aperture while applying an external electrostatic potential to the specimen. A simple analysis using geometrical optics for this phenomenon suggests that the distortion of the image can be correlated to the deflection of the electron beam by the electrostatic field at the level of a specimen.

The analysis suggests that the image distortion is proportional to the electrostatic field strength and sensitive enough to detect a potential difference less than 1 eV/μm at the level of a specimen. The method may be used not only to observe the specimen in focused condition but also to measure the electrostatic field quantitatively. This method can be applied to the observation of the electric/magnetic field distribution by a conventional TEM without any additional apparatus.

Experiments

The specimen used in this work was a commercial GaP light-emitting diode (LED) as shown in Fig. 1. The specimen was fixed to the Kamino holder [4] that was originally designed as a heating holder. The external voltage was applied to the specimen through the electrodes of the holder. The detail of the specimen preparation is described elsewhere [3]. Before applying electron holography in a FEG-TEM, the overall morphology of the specimen was observed in a TEM Hitachi H-9000 NAR equipped with an ordinary LaB_6 thermal emission electron gun at an accelerating voltage of 300kV. Applying a reverse bias voltage to the p-n junction of the LED chip, the area along the edge of the specimen where the p-n junction was located as indicated by the arrow in Fig. 1, was observed in the very low magnification mode, called "Low Mag" mode (hereinafter referred to as "LM" mode), positioning the SAD aperture in the image.

Another type of specimen was also prepared to allow a more clear geometrical analysis. Two electrodes made of Al plates with a thickness of 20μm were fixed to the respective electrodes of the specimen holder and carefully positioned with a space of 20μm in between as shown in Fig. 2. The correlation between the shift of the image and the deflection angle of the electron beam was measured as a function of the applied voltage between the two electrodes in the H-9000 NAR.

Results and Discussion

As a practical method of rough alignment of the beam tilt in the LM mode, the shadow image of the SAD aperture was observed. As shown in Fig.3, during the alignment procedure, a local distortion of the edge shape of the SAD aperture near the reverse biased p-n junction of the specimen was observed without affecting the image of the specimen at all. The continuous circular edge shape of the aperture was observed when the external voltage was not applied (Fig. 3(a)). However, a discontinuity of the edge shape appeared when the reverse bias was applied as shown in Fig.3(b) and (c). The distortion expanded when increasing the applied voltage. The above-mentioned phenomenon was explained using simple geometrical optics as follows.

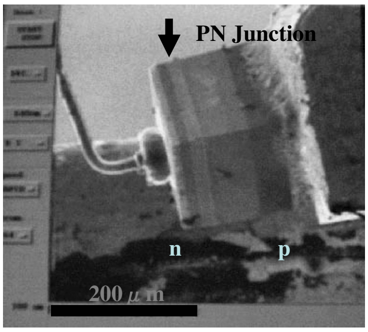

Fig.1 A scanning ion microscopic (SIM) image of the GaP light-emitting diode (LED) chip used in this study.

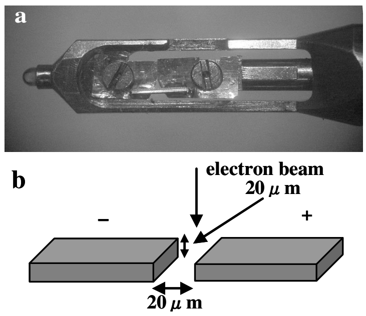

Fig. 2 The two electrodes fixed on the specimen holder (a) and the schematic drawing of them (b).

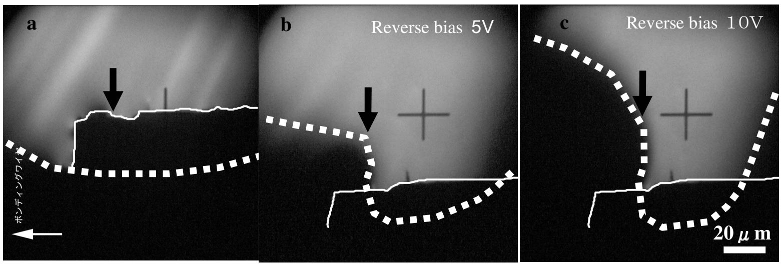

Fig. 3 The observed local distortion of the SAD aperture image near the reverse biased p-n junction of the specimen at 0V (a), 5V (b) and 10V(c), respectively. The solid lines and the broken lines indicate the edge shape of the specimen and the SAD aperture, respectively. The arrows indicate the position of the p-n junction.

In the LM mode, the image of the specimen is formed by the intermediate lens, and the objective lens is usually turned off or only weakly activated. We discuss first the condition in which the objective lens is completely turned off and then the case when the objective lens is weakly activated. The ray diagram in the first condition is shown in Fig. 4. The SAD aperture is located between the specimen and the intermediate lens. If the divergence of the electron beam is relatively small, for example of the order of 10^{-4} rad, the shadow image of the SAD aperture ($\boldsymbol{R_{ap}}$ in radius) is projected on the image plane with a radius $\boldsymbol{R_{im} = R_{ap} M_i}$, where $\boldsymbol{M_i}$ is the magnification of the intermediate lens. When the electron beam is deflected by the electrostatic potential of the specimen at an angle θ, the electron beam from the specimen between A and B is obstructed by the SAD aperture. The electron beam obstructed by the SAD aperture has been imaged between A' and B' on the image plane of the intermediate lens. This means that the edge of the shadow image of the SAD aperture will move from A' to B'. This will be observed as a shift of the aperture edge in the image. The distance of A-B, i.e. $\boldsymbol{d}$, can be calculated by the deflection angle θ and the distance $\boldsymbol{a}$ between the SAD aperture and the specimen. The distance $\boldsymbol{d}$ will be enlarged by the intermediate lens to become $\boldsymbol{D = a\, \theta\, M_i}$ at the image plane and then enlarged or reduced to be imaged on the fluorescence screen by the following lens system with a magnification $\boldsymbol{M_p}$.

In the case of Hitachi H-9000 NAR, the objective lens is weakly activated in the LM mode. The ray diagram in this condition is shown in Fig.5. In the LM mode with the weakly activated objective lens, the back focal plane of the objective lens is located slightly lower than the front focal plane of the intermediate lens. For simplicity, the objective lens plane is considered to be approximately in the plane of the specimen, because a very low current is applied to the objective lens, for example, in the case of Hitachi H-9000 NAR, one twentieth of the ordinary imaging mode. When the objective lens is in the same plane as the specimen, the image of the specimen is formed at the same magnification as if there were no objective lens. However, the electron beam passing through the specimen will be focused almost to one point on the back focal plane of the objective lens and then diverge. The area on the specimen through which pass the electrons passing through the SAD aperture hole is the reverse projection of the SAD aperture on the specimen surface as indicated by the thick arrows in Fig. 5. The radius R_{ob} of the reversely projected SAD aperture is calculated to be $R_{ob} = R_{ap} f_o / d_{ap}$, where R_{ap} is the radius of the SAD aperture, f_o is the focal length of the objective lens and d_{ap} is the distance between the back focal plane of the objective lens and the SAD aperture. The shadow image radius R_{im} of the SAD aperture in the image plane of the intermediate lens is the magnified image of this reverse projection by the intermediate lens; it is given by: $R_{im} = R_{ap} M_{ap} M_i$, where M_{ap} is f_o / d_{ap}.

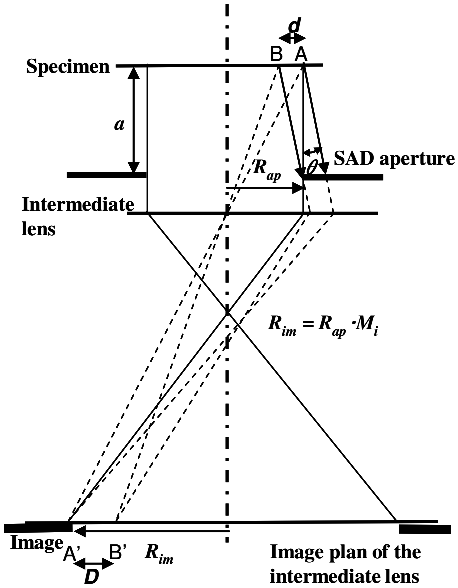

Fig. 4 Ray diagram of the LM mode when the objective lens is turned off.

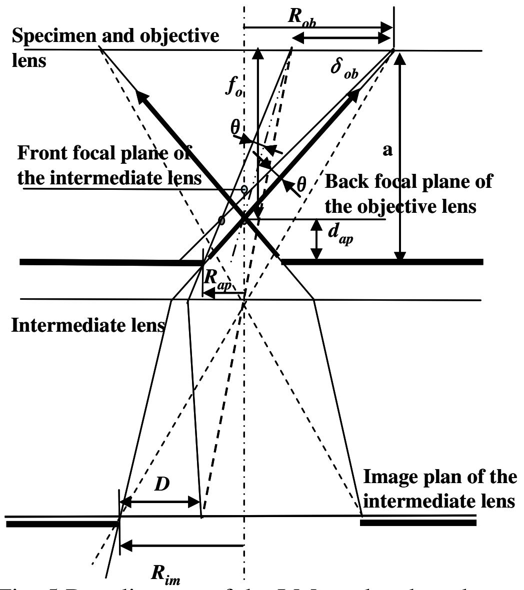

Fig. 5 Ray diagram of the LM mode when the objective lens is weakly activated.

When the electron beam is deflected by the electrostatic potential at an angle θ, the focal point of the electron beam on the back focal plane of the objective lens is displaced by $f_o\ \theta$. On the surface of the specimen, the area on the specimen through which pass the electrons passing through the SAD aperture hole will change. The shift of the aperture edge δ_{ob} is calculated to be $\delta_{ob} = f_o\ \theta\ (d_{ap} + f_o) / d_{ap}$. This equation can be rewritten as $\delta_{ob} = a\ \theta f_o / d_{ap}$, because $a = d_{ap} + f_o$. The shift δ_{ob} is enlarged onto the image plane of the intermediate lens with the magnification M_i. Thus the shift of the aperture edge D is calculated to be $D = a\ \theta\ M_{ap}\ M_i$. The value of M_{ap} can be determined by comparing the real size with the imaged size of the SAD aperture diameter.

The analysis using simple geometrical optics shows in both cases, i.e., when the objective lens is turned off or weakly activated, that the shift of the shadow image of the SAD aperture edge is proportional to the deflection angle of the electron beam by the electrostatic potential at the specimen level.

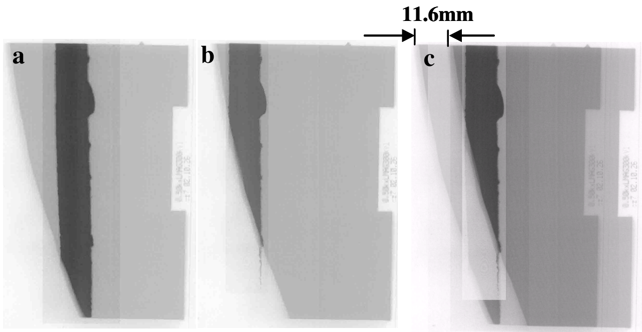

Fig. 6 SAD aperture image observed between the two electrodes superimposed onto the aperture image without the electrodes at 0V (a) and 2V (b), respectively. The shift of the aperture image was measured on the photographic films aligning the electrodes image with each other as shown in (c).

The amount and proportionality of the image shift which depends on the applied electrostatic field were examined by inserting the two electrodes at the specimen position as shown in Fig. 2. The deflection angle of the electron beam was measured to be 1.67×10^{-4}rad at an applied voltage of 20V (1kV/m) by observing the shift of the center spot of the diffraction pattern. The shift of the SAD aperture image, which depends on the applied voltage, was observed at a magnification of 500, which corresponds to $\boldsymbol{M_i M_p}$. The magnification $\boldsymbol{M_{ap}}$ in this condition was measured to be 12.5. The shift of the image estimated from the deflection angle was 8.1mm/V on the fluorescence screen. The shift of the aperture image was measured up to 2V on the fluorescence screen as shown in Fig. 6. The rate of image shift as a function of applied voltage was determined to be 6.2 mm/V, which is in good agreement with the predicted value, if one takes into account the reliability of the magnification of the TEM in the LM mode.

The electron optics used in this method is similar to the Foucault mode of Lorenz microscopy, though the intermediate lens and the SAD aperture are used instead of the objective lens and the objective aperture. The Foucault mode which can detect the deflection of the electron beam as the image contrast is not suitable to quantitative analysis of the image because the intensity variations in the image are extremely sensitive to the exact positioning of the aperture [2]. In our method, the deflection of the electron beam is measured as the distance of the aperture image shift, quantitatively, and the deflection direction can also be determined by changing the direction of the aperture edge. Though our method was developed to examine the electrostatic field at the specimen level, one can point out that it is possible to detect the magnetic field as well, since the method simply detects the deflection of the electron beam at the specimen level**.** The sensitivity of the deflection angle is of the same order as the divergence of the electron beam. Even though the thickness of the specimen is of the order of 100nm, a potential difference less than 1V/μm can be detected with this method. The detection of the electrostatic and/or magnetic field in this method is one dimensional, because the shadow image of the aperture edge is used. However, this limitation can be easily removed; for instance if the aperture is scanned across the image or if a square lattice shaped mesh with a size of a few microns is used instead of the SAD aperture.

Our method can also be performed in a FEG-TEM equipped with an electron bi-prism because the electron bi-prism is placed at the same position as that where the SAD aperture was placed. The distortion of the shadow image of the bi-prism had been observed in an electron holography observation [5]. The narrow and sharp image of the bi-prism is more suitable than the irregular edge shape of the SAD aperture for quantitative measurement. It is difficult to distinguish the effect of the thickness change on the image from that of the potential distribution by electron holography. Though our method is limited to the LM mode, it is an advantage to be able to detect the genuine electrostatic and/or magnetic field distribution at the specimen level.

Summary

The image distortion of the SAD aperture in the LM mode can be used to measure the deflection of the electron beam at the specimen level by the electrostatic field. The sensitivity of this technique is sufficient to detect a deflection of the electron beam of the order of 10^{-4} rad quantitatively. Though the method is limited to the LM mode, it is the simplest method to observe and measure the electrostatic and/or magnetic field with a conventional transmission electron microscope without any additional apparatus. Easy to implement modifications of this method will allow to observe the two dimensional distribution of the electrostatic and/or magnetic field at the specimen level.

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