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Variable magnification dual lens electron holography for semiconductor junction profiling and strain mapping

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ABSTRACT

Dual lens operation for electron holography, which was developed previously (Wang et al., Ultramicroscopy 101 (2004) 63–72; US patent: 7,015,469 B2 (2006)), is re-investigated for bright field (junction profiling) and dark field (strain mapping) electron holography using FEI instrumentation (i.e. F20 and Titan). It is found that dual lens operation provides a wide operational range for electron holography. In addition, the dark field image tilt increases at high objective lens current to include Si ⟨0 0 4⟩ diffraction spot. Under the condition of high spatial resolution (1 nm fringe spacing), a large field of view (450 nm), and high fringe contrast (26%) with dual lens operation, a junction map is obtained and strain maps of Si device on ⟨2 2 0⟩ and ⟨0 0 4⟩ diffraction are acquired. In this paper, a fringe quality number, N', which is number of fringe times fringe contrast, is proposed to estimate the quality of an electron hologram and mathematical reasoning for the N' number is provided.

1. Introduction

In the semiconductor industry, junction profiling and strain mapping at high spatial resolution is critical to characterize semiconductor devices improvement schemes. In recent years, stressors have been incorporated into device structures to change the semiconductor lattice constant in the channel region, thereby enhancing hole/electron mobilities. The extra process steps involved have increased development and manufacturing costs. One way to minimize the development cycle times is to monitor, on a nanometer scale, the changes in the channel deformation with process changes.

In 2008, Hytch et al. [1] reported that dark field holography can provide a promising path to nanometer scale strain mapping. Cooper et al. [2,3] reported using dark field holography to measure strain for different process conditions On the instrumentation side, Sickmann et al. [4] reported a procedure using a single lens (objective) to achieve different field of view and fringe spacing for electron holography.

Typically, electron holography is practiced on commercially available TEMs using a single lens—either the Lorentz or the objective lenses. In this paper, we only discuss the lens or lenses between object and biprism, unless otherwise mentioned. Such a single lens operation limits the range of the fringe spacing and fringe width (interference width) relative to specimen. In addition, it is generally found that for dark field electron holography with Lorentz lens only operation, the dark field imaging tilt is limited. This limits the reflections that can be used to create holograms—e.g. the ⟨0 0 4⟩ reflection for Si can be hardly reached.

Previously, a procedure using a dual lens operation for electron holography was published and patented using a JEOL 2010F field emission transmission electron microscope [5,6]. It was shown that the dual lens procedure resulted in a variable fringe spacing and width (also known as interference width) relative to the sample, which allowed high spatial resolution junction profiling and strain mapping to be obtained.

In this paper, we will describe a dual lens operation results obtained on FEI microscopes using the objective and a Lorentz lenses. We will also show that the procedure results in high spatial resolution for both junction profiling and strain mapping. We will also show that with the dual lens operation, large tilt dark field holograms can be achieved.

2. Theory of electron holography and dual lens operation

2.1. Basic equations for electron holography

In electron holography, three parameters are critical: fringe width for field of view, fringe spacing for spatial resolution, and fringe contrast for signal to noise ratio. Missiroli et al. [7] introduced the equations that describe the first two parameters and in the earlier paper [5], we introduced the equation describing the third

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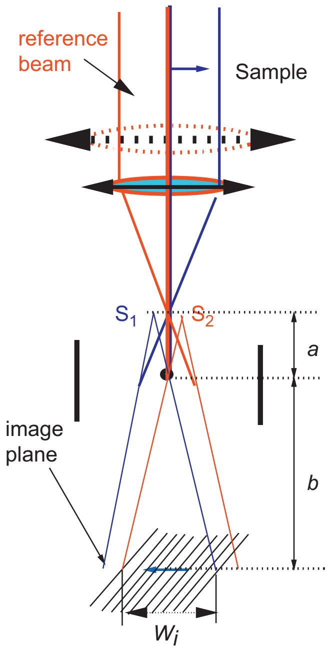

Fig. 1. Electron hologram formation using objective minilens only. The interference pattern with fringe spacing, σ_i and fringe width W_i are formed by two virtual sources, S_1 and S_2.

parameter. In the following section, we will briefly review these equations and their implications on electron holography operation.

As illustrated in Fig. 1, an off-axis electron hologram can be thought of as being formed from two virtual sources, S_1 and S_2, of finite size (δ) positioned above the biprism and separated by a distance d. The fringe spacing or periodicity, σ_i, and fringe width, W_i, at the image plane can be described [7–10]:

$$\sigma_i = \frac{\lambda}{2\gamma_o V_b}\left(1+\frac{b}{a}\right) \tag{1}$$

and

$$W_i = 2\gamma_o V_b b - 2r_b\left(1+\frac{b}{a}\right), \tag{2}$$

where γ_0 is related to accelerating voltage of electron beam and other parameter of the microscope setting, r_b is biprism radius, a is the distance between the virtual sources and biprism position, b is the distance between image plane and the biprism position, λ is the wavelength of the electron beam, and V_b is the biprism voltage. Relative to the object (sample), the fringe spacing, σ_o, and width, W_o, are expressed as [8–10]

$$\sigma_o = \frac{\sigma_i}{M_O} \tag{3}$$

and

$$W_o = \frac{W_i}{M_O}, \tag{4}$$

where M_O is the magnification of the imaging lens(es).

The standard deviation (noise), σ_p, in a phase map derived from a hologram is as

$$\sigma_p \propto \frac{1}{\eta\sqrt{P_{m,n}}}, \tag{5}$$

where η is the fringe contrast, $P_{m,n}$ is the number of electrons at pixel m,n location of the CCD detector [11]. Thus, the contrast of a hologram is an important parameter which determines the noise level of the resulting data. Using Lichte's notation [8–10] and from wave optics [12], one can derive the fringe contrast, η, as

$$\eta = \frac{I_{max}-I_{min}}{I_{max}+I_{min}} = \frac{\sin(\beta)}{\beta}, \tag{6}$$

where

$$\beta = \frac{2\pi\delta}{\lambda}\frac{\gamma_0 b}{a+b}V_b + \beta_0, \tag{7}$$

where δ is the dimension of the source. In Eq. (7), β_0, an experimentally determined parameter used for data fitting, is added on [13], in addition to the first term derived from the wave optics [5].

2.2. Fringe quality number

To get useful electron hologram, we need reasonable fringe contrast (20–40%) and high number of fringes in the hologram. The number of fringes (fringe number) can be calculated as following:

$$N = \frac{W_o}{\sigma_o} = \frac{W_i}{\sigma_i}. \tag{8}$$

Based on Eqs. (1)–(4) and (6)–(8), increasing the biprism voltage increases the number of fringes and decreases the fringe contrast. Both fringe number and fringe contrast have a strong dependence on biprism voltage and either can be used to estimate the quality of an electron hologram. Since these two numbers are inversely related to the biprism voltage, the product of these two numbers can be used to estimate the quality of the hologram. We define a fringe quality number, N', as

$$N' = N\eta. \tag{9}$$

We can mathematically prove that there is a maximum N', where a change of N' with biprism voltage is small. If we ignore the second term in Eq. (2), the number of fringes is

$$N = C_1 V_b^2. \tag{10}$$

Assuming $\beta = \alpha + \beta_0$, where $\alpha = C_2 V_b$, one can derive the contrast, η, within the range of 0% and 70%, as a linear expansion to the first order:

$$\eta = \frac{\sin\beta}{\beta} \approx \frac{\partial\eta}{\partial\beta}\Delta\beta + \frac{\sin\beta_1}{\beta_1} = k\alpha + b_1, \tag{11}$$

where $k \sim -0.414$ and $b_1 \sim 1.28 - 0.414\beta_0$ (see Appendix A). The fringe quality number, N', can be rewritten as

$$N' = \frac{C_1}{(kC_2)^2}(\eta - b_1)^2\eta. \tag{12}$$

To obtain η_{max}, where N' is a maximum, a derivative of N' over η can be calculated as

$$\frac{\partial N'}{\partial\eta} = \frac{C_1}{(kC_2)^2}(\eta - b_1)(3\eta - b_1) = 0 \tag{13}$$

and

$$\eta_{max} = \frac{1}{3}b_1 \sim \frac{1}{3}(1.28 - 0.414\beta_0). \tag{14}$$

Since the N' near its maximum value is less dependent on η or V_b, N' can be used to estimate the quality of a hologram.

2.3. Bright field holography for junction profiling

Junction profiling by electron holography is accomplished by superimposing electron beam passing through the sample with the electron beam passing through the vacuum (Fig. 1). The intensity of the wave function after biprism can be written as

$$I = A_0^2 + A^2(\vec{r}) + 2\eta A(\vec{r})A_0\ \cos[2\pi q_c r + \varphi(\vec{r}) + \varphi_0]. \tag{15}$$