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Estimation of electron probe profile from SEM image through wavelet multiresolution analysis for inline SEM inspection

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Abstract

We propose an analytical estimation method of the electron probe profile from an SEM image through the wavelet analysis of the multiscale information for inline SEM inspection. Defocused electron probe profiles are calculated based on wave optical theory. The calculated profiles are well approximated with the distributions composed of several Gaussian distributions with different center positions and variances. Analytical equations to estimate standard deviations of blurring Gaussian functions included in the defocused electron probe profile from a sequence of wavelet transform modulus maxima are derived. By using a noisy blurred step edge signal, the estimation accuracy was evaluated as a function of *SNR* with the standard deviation of blurring Gaussian function as a parameter. The accuracy of better than 15% is obtained when the *SNR* becomes larger than 10. Our analytical estimation method is applied to the simulated secondary electron intensity profile blurred with the defocused electron probe profile. The probe profile similar to the calculated one is estimated.

Keywords: Wavelet multiresolution analysis; SEM image; Probe profile estimation; Electron probe; Inline SEM inspection

1. Introduction

As integrated circuit fabrication processes continue to increase in complexity, strategies, and software methods for manufacturing management have been identified as critical for maintaining productivity. The management must comprehend integrated circuit design, defects, parametric data, and electrical test information to recognize process trends and excursions to facilitate the rapid identification of yield detracting mechanisms.

As physical device dimensions and corresponding defect dimensions continue to shrink, the defect detection is one of the difficult challenges for yield enhancement technologies in semiconductor manufacturing [1]. Detecting defects associated with high aspect ratio contacts, and combinations of trenches and vias in dual-damascene structures will continue to be difficult defect detection challenges. More specifically, the detection of via defects within the structure of a damascene trench on a process layer containing up to 10 billion similar structures will continue to be the grand challenge. The challenge is complicated by the simultaneous need for high sensitivity and high throughput.

High aspect ratio inspection (HARI) is defined as the detection of defects occurring deep within structures having depth to width ratios greater than 3. HARI defects relate contact and via shape (defined at the bottom of the feature: highest resistive point), size, and remaining material. HARI defects are already considered killers at any process stage. Process verification for HARI defects usually refers to scanning electron microscope (SEM)-type tools.

In the use of SEM imaging to inspect wafers for HARI defects, voltage-contrast (VC) imaging of patterned wafer

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samples has become an important technique in recent years. The VC images result from the spatial variation of a sample's charging voltage generated by electron-beam irradiation, which depends on the resistance of the irradiated portion. Thus, VC images can be effectively used to find electrical failures in semiconductor devices such as resistance of contacts and vias, which cannot be recognized in an optical inspection system [2]. For high sensitivity and high throughput of the SEM imaging system, the system requires a high-current primary electron beam with an appropriate irradiation electron beam energy. The VC imaging method using single scan of high-current electron beam has been developed [2]. It has been reported that this imaging method is capable of detecting 2 nm oxide remaining at the bottom of via. The electron optics and secondary electron (SE) detection system in this imaging method have been developed [3,4]. The electron optics adopts the retarding system where the primary electron beam is rapidly decelerated near the sample surface to reduce the influence of the Coulomb effect and lens aberrations, resulting in high spatial resolution even when using a high-current electron beam. However, the electron optical focusing conditions such as current of probe-forming lenses change over time: the defocusing arises. Thus, in order to maintain the high spatial resolution, it is necessary to evaluate the irradiating electron probe profile frequently. In the retarding electron optical system, it is difficult to use the knife-edge method for inline SEM inspection that is usually used to evaluate the electron probe profile.

We have tried to estimate the electron probe profile from an SEM image by using wavelet multiresolution analysis for inline SEM inspection [5]. In the proposed estimation method, we obtain the relation between the electron beam diameter (the standard deviation of Gaussian profile) and the maximum wavelet coefficient from the wavelet multiresolution analysis of simulated SE profiles observed by the electron probe with Gaussian profiles beforehand. Then the SE intensity profile for a test pattern is extracted from a real SEM image. The SE profile is decomposed by the wavelet multiresolution analysis. By comparing, the obtained maximum wavelet coefficient of SE profile with the relation between the electron beam diameter and the maximum wavelet coefficient, the electron probe profile is estimated. Since the target for the method is to estimate the diameter of main lobe in the electron probe profile, it is difficult to estimate the electron probe profile with fringes by using the previous method (see Fig. 1e, for example).

In this paper, we propose an analytical estimation method of the electron probe profile from an SEM image through the wavelet analysis of the multiscale information for inline SEM inspection. The paper is organized as follows. In Section 2, we calculate electron probe profiles for different defocus values. In Section 3, we describe the analytical estimation method from a sequence of wavelet transform modulus maxima. In Section 4, we apply our proposed analytical estimation method to the simulated SE intensity profile. In Section 5, we summarize the results.

2. Electron probe profiles for different defocus values

We calculate electron probe profiles for different defocus values based on wave optical theory [6].

The primary wave function and the electron beam current density distribution in the specimen plane are calculated under the following assumptions:

1. The electrons are emitted from a point source with a well-defined initial energy.
2. Only the effects of spherical aberration and diffraction are considered, since spherical aberration or diffraction aberration becomes dominant in the electron probe profile, when the electron optical focusing conditions deviate from the optimum [3]. Under the optimum focusing conditions, the chromatic aberration plays significant role in the electron probe profile.

Then the amplitude $\psi(r)$ and intensity $j(r)$ of the electron probe profile are given by the following equations:

$$\psi(r) = \frac{2\pi}{\lambda}\sqrt{\frac{I_0}{\pi\alpha_0^2}}\int_0^{\alpha_0} \exp(\mathrm{i}W(\alpha))J_0\left(\frac{2\pi r\alpha}{\lambda}\right)\alpha\,\mathrm{d}\alpha, \tag{1}$$

$$j(r) = |\psi(r)|^2, \tag{2}$$

where λ denotes the deBroglie wavelength of the electrons, I_0 the primary beam current, and α_0 the aperture-limiting semi-angle. $W(\alpha)$ is given by the following equation:

$$W(\alpha) = \frac{2\pi}{\lambda}\left(C_S\frac{\alpha^4}{4} + \Delta z\frac{\alpha^2}{2}\right), \tag{3}$$

where C_S denotes the spherical aberration coefficient, and Δz is the defocus.

Fig. 1 shows calculated electron probe profiles $j(r)$s for a 500 V SEM with $\lambda = 54.8$ pm, $C_S = 1.9$ mm [7], and $\alpha_0 = 35$ mrad, where $j(r)$ is normalized. The defocus Δz varies from +200 nm to −600 nm in increments of 200 nm. It is seen that the half-width of the central peak (main lobe) decreases with varying defocus from +200 nm to −600 nm, whereas the amplitude of the fringes at higher values of r becomes prominent.

We try to approximate the defocused electron probe profile with the distribution composed of several Gaussian distributions with different center positions and variances σ^2s. The result is shown in Fig. 2, where the profile (solid line) with $\Delta z = -400$ nm is approximated. The broken line indicates the approximated profile composed of three Gaussian distributions with [position (nm), σ(nm)] = (0, 0.62), (2.45, 0.5), and (4.5, 0.5). It is seen that the defocused profile is close to the approximated profile. Thus the defocused profile is well approximated with Gaussian distributions.