Paper:

Simulation-Based Analysis of Influence of Error on Super-Resolution Optical Inspection

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Microfabricated structures such as semiconductors and MEMS continue shrinking as nanotechnology expands, demand that measures microfabricated structures has risen. Optics and electron beam have been mainly used for that purpose, but the resolving power of optics is limited by the Rayleigh limit and it is generally low for subwavelength-geometry defects, while scanning electron microscopy requires a vacuum and induces contamination in measurement. To handle these considerations, we propose optical microfabrication inspection using a standing-wave shift. This is based on a super-resolution algorithm in which the inspection resolution exceeds the Rayleigh limit by shifting standing waves with a piezoelectric actuator. While resolution beyond the Rayleigh limit by proposed method has been studied theoretically and realized experimentally, we must understand the influence of experimental error factors and reflect this influence in the calibration when actual application is constructed. The standing-wave pitch, initial phase, and noise were studied as experimental error factors. As a result, it was confirmed that super-resolution beyond the Rayleigh limit is achievable if (i) standing-wave pitch error was 5% when standing-wave pitch was 300 nm or less and (ii) if initial phase error was 30° when standing-wave pitch was 300 nm. Noise accumulation was confirmed in studies of the noise effect, and a low-pass filter proved effective against noise influence.

Keywords: standing-wave illumination, image reconstruction, super-resolution

1. Introduction

According to the International Technology Roadmap for Semiconductors (ITRS) roadmap [1], a next-generation semiconductor defect inspection system is urgently demanded, and the challenges for defect detection increase exponentially with shrinking design, such as sub-100-nm nodes. A key area where improvement is needed is defect detection of semiconductor wafers [2]. Wafer defects include random defects such as killer particles, clusters, and scratches that degrade chip performance and process yield in the semiconductor manufacturing process. Especially, improved inspection of patterned wafers is a necessity for next-generation semiconductors.

Optical methods and electron beams are conventionally used in semiconductor wafer inspection [3]. However, with the continuous miniaturization of interconnects, optical inspection becomes less useful because of its diffraction limit. On the other hand, Electron beams lack utility for wider wafer inspection because of their low throughput. We think that optical inspection has greater potential than Scanning Electron Microscope (SEM) inspection because optical inspection is nondestructive and has high throughput, so we have focused our work in optical inspection. Resolution and defect detection beyond the Rayleigh limit are now required in optical patterned wafer inspection due to accelerating pattern miniaturization and advanced semiconductor device development [4].

A potential solutions in semiconductor optical inspection is the use of shorter wavelengths, studied as a measure against device miniaturization, but wavelength shortening is too limited to meet the challenges involved, so we have developed super-resolution inspection technique. Namely, when a pattern is miniaturized and made dense, light reflected from the wafer becomes weak, and the captured images becomes dark with low contrast; hence, a high-sensitivity method that can obtain a lot of optical information must be developed [5]. Our super-resolution inspection combines a standing-wave illumination shift with dark-field imaging to deliver optimal sensitivity in critical defect detection at the sub-100-nm level and beyond without compromising throughput [6, 7]. The standing-wave illumination shift enables micro structures to be optically resolved as no conventional application can. Nano-scale illumination shifts and super-resolution postprocessing are keys in enhancing resolution and enabling higher defect detection sensitivity, e.g., experimentally achieved two-dimensional super-resolution [8]. The sections that follow clarify the influence on super-

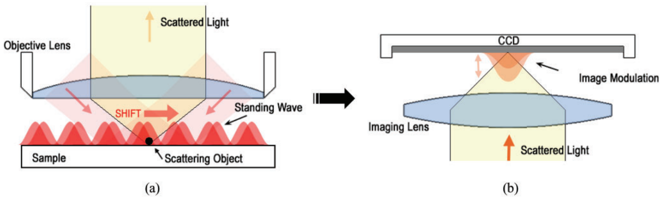

Fig. 1. Standing-wave illumination shift and scattered-light modulation.

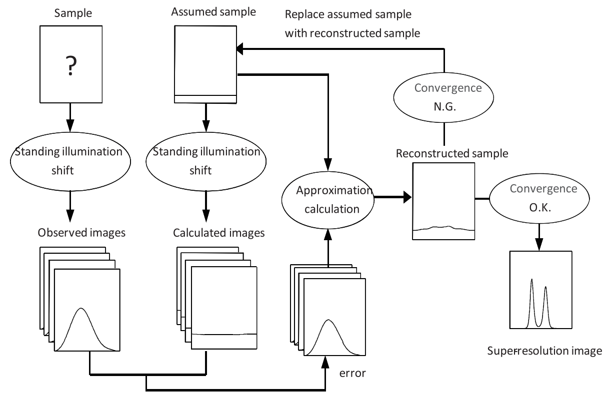

Fig. 2. Super-resolution postprocessing.

resolution results of different types of errors in standing-wave illumination parameters and noise included in optical image detection.

2. Methodology

2.1. Standing-Wave Illumination Shift and Scattered-Light Modulation

As shown in **Fig. 1**, standing-wave illumination is generated by 2-beam interference scattered by the sample surface and focused on the CCD imaging surface through an imaging lens. The standing wave is shifted on the nanoscale by the phase difference between the 2 beams in illumination (**Fig. 1 (a)**). Scattered light is then modulated when standing-wave illumination shift (**Fig. 1 (b)**). A super-resolution image of scattering efficiency is calculated from multiple images by a super-resolution image reconstruction algorithm.

2.2. Super-Resolution Image Reconstruction Algorithm for Postprocessing

In the super-resolution postprocessing shown in **Fig. 2**, the sample is first lit with standing-wave illumination and multiple images are experimentally observed with the standing-wave shift. Calculated images are then computed based on Fourier optics. The error between observed and calculated images is approximately fed back to an assumed sample to obtain a reconstructed sample. Image reconstruction is iteratively calculated with successive approximation until error converges. Standing-wave illumination nanoshifts modulated on a half-wavelength scale include high-frequency spatial information, and this causes a change to scattered-light images. We expect to achieve super resolution by feeding back errors in scattered-light images to sample distribution and reconstructing sample distribution with successive approximation.

As shown in **Fig. 3**, when two point samples to be observed are close enough, the two points cannot be distinguished in the observed image. The sample is illuminated by the standing wave, producing multiple modulated scattered-light images, which are postprocessed so that the two point samples are clearly resolved as shown at lower right, achieving super resolution.

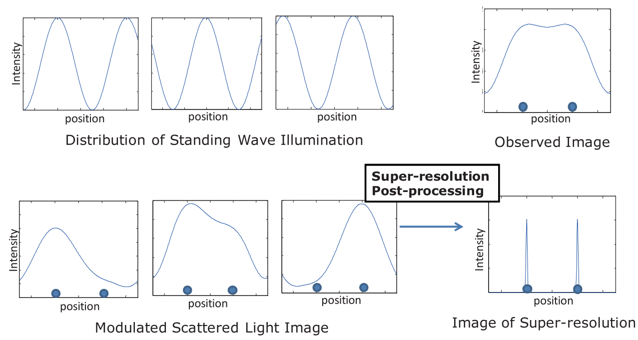

Fig. 3. Super-resolution.

3. Resolution Property Considering Error of Standing-Wave Illumination Parameters

In experimental super-resolution, standing-wave illumination error factors are expected to influence resolution results, as detailed below. Standing-wave illumination pitch and phase are considered here as error factors.

3.1. Error-Free Super-Resolution

Figure 4 shows an employed sample and a super-resolution image of sample for verifying resolution properties considering standing-wave illumination parameter errors using a continuous sample more actual than discrete as shown in **Fig. 3**. Simulation conditions are shown in **Table 1**.

The employed sample (**Fig. 4 (a)**) is observed as shown **Fig. 4 (b)** in normal uniform illumination. The sample structure is not resolved in **Fig. 4 (b)**, but is clearly resolved by the super-resolution image in **Fig. 4 (c)**. Super-resolution postprocessing resolves both the discrete sample as shown in **Fig. 3** and continuous distribution as shown in **Fig. 4 (a)**.

3.2. Error Factor: Standing-Wave Illumination Pitch

Resolution properties are examined when standing-wave illumination pitch is an error factor. **Table 1** lists simulation conditions. **Fig. 5** shows super-resolution results when minute error exists between the standing-wave

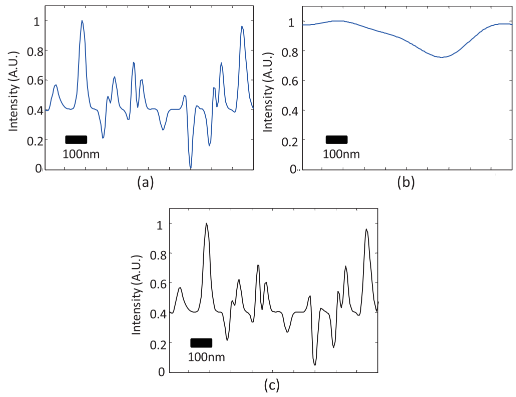

Fig. 4. Employed continuous sample (a) sample, (b) observed image by uniform illumination, (c) super-resolution image.

Table 1. Simulation conditions.

Wavelength of source (nm)	488
Standing-wave illumination pitch : T (nm)	300
NA of objective	0.95
Rayleigh limit (nm)	313
Shift times	10
Shift step size (nm)	30
Iteration times	1,000,000

pitch used in super-resolution postprocessing (300 nm) and the actual standing-wave pitch. Resolution properties deteriorate as the error increases. It settles to the wrong solution from the surrounding part of the resolving area. It seems that accumulating error caused by the rupture of information in the boundary of resolving area is a cause of wrong solution. The deterioration of resolution properties depends on iteration times and NA, etc. It is necessary to investigate the detailed determination factors which decide the range of the area where the resolving image can be appropriately done in the future.

Resolution is quantitatively evaluated by the correlation coefficient between the sample and super-resolution result. **Fig. 6** shows results of examining the correlation coefficient for a standing-wave pitch of 250 nm, 300 nm, or 360 nm. The smaller the standing-wave pitch, the better the resolution, e.g., standing-wave pitch error is 5% for a standing-wave pitch of 300 nm, so super-resolution is achieved using the correlation coefficient at the Rayleigh limit as a resolution index.

3.3. Error Factor: Phase of Standing-Wave Illumination

Resolution properties when the standing-wave illumination phase is examined under the simulation conditions in **Table 1**. **Fig. 7** shows super-resolution results when there is difference between the standing-wave phase used by super-resolution postprocessing and the actual standing-wave phase. Note the similarity between **Figs. 5** and **7**.

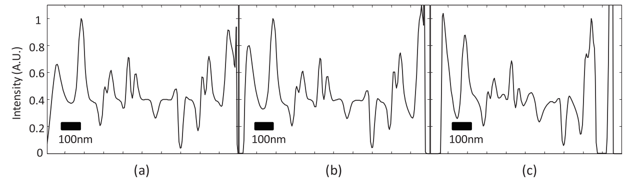

Fig. 5. Super-resolution postprocessed images using a pitch of 300 nm (a) actual pitch of 302 nm, (b) actual pitch of 305 nm, and (c) actual pitch of 315 nm.

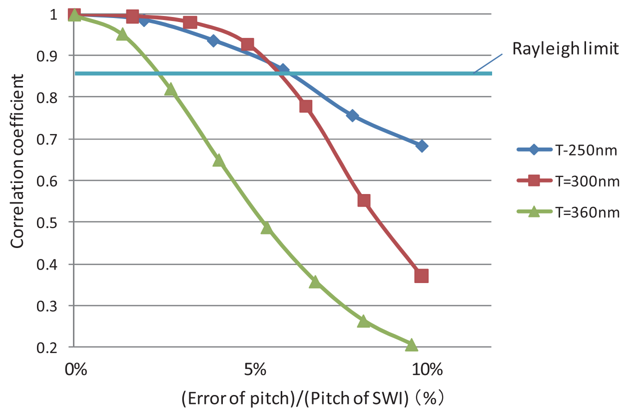

Fig. 6. Correlation coefficient with standing-wave illumination pitch mismatch.

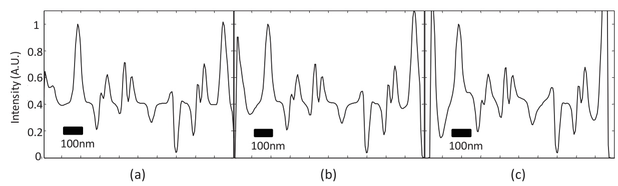

Fig. 7. Super-resolution postprocessed images with phase differences of (a) 2°, (b) 6°, and (c) 18°.

Quantitative evaluation is done using the correlation coefficient. **Fig. 8** shows results for a standing-wave pitch of 250 nm, 300 nm, 360 nm, 420 nm. The smaller the standing-wave pitch, the better the resolution. Resolution properties depend on the standing-wave pitch, e.g., the phase difference is 30° at a standing-wave pitch of 300 nm and super-resolution can be achieved by using the correlation coefficient at the Rayleigh limit as a resolution index.

4. Resolution Properties Considering Noise

The influence that the noise brought to the resolution properties is investigated. And a low-pass filter is introduced as a counter measure to the effect of noise. We first step, put random noise containing all frequencies in an observed image with optics, with the results shown in **Figs. 9** and **10**. **Fig. 9** shows how noise accumulates. **Fig. 9 (A)** shows an employed periodical sample (150 nm pitch). Observed sample images with the standing-wave illumination are shown in **Fig. 9 (B)**. **Fig. 9 (B)(a)** shows

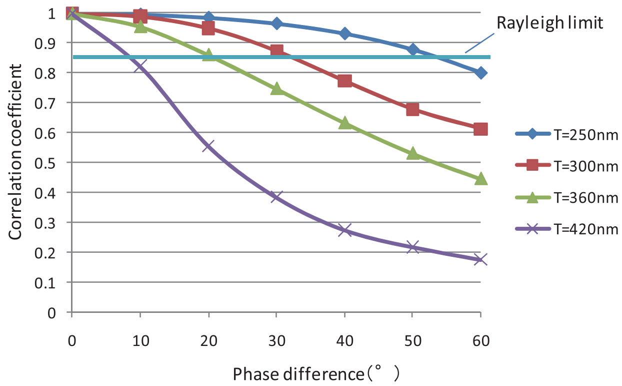

Fig. 8. Correlation coefficient with phase difference of standing-wave illumination.

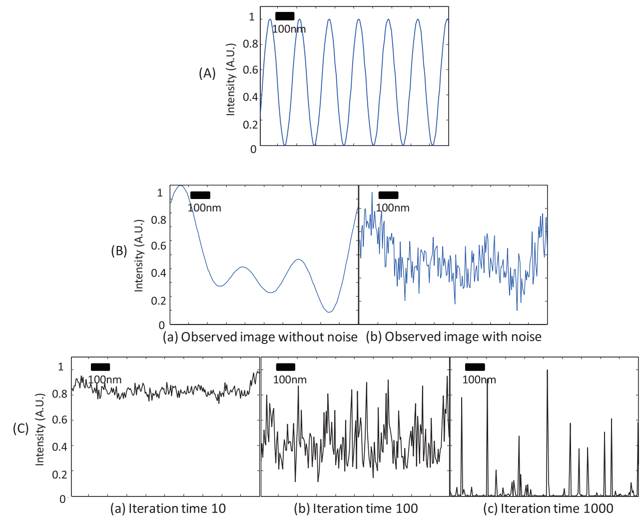

Fig. 9. Accumulation of noise (A) sample, (B) observed images with standing wave, (C) super-resolution postprocessed images without filter.

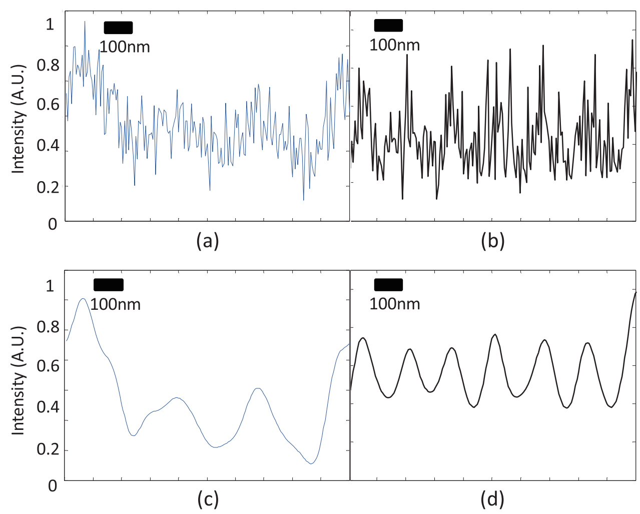

Fig. 10. Effect of low-pass filter, (a) observed image with noise, (b) super-resolution postprocessed image without filter, (c) filtered image on (b), (d) super-resolution postprocessed image without filter.

the observed image without noise. An image with 10% random noise added is shown in **Fig. 9 (B)(b)**. Super-resolution postprocessing was done with random noise added images like **Fig. 9 (B)(b)**. **Fig. 9 (C)** shows super-resolution-postprocessed images. Iterations number 10, 100, and 1,000 in **Fig. 9 (C)(a)**, **(C)(b)**, and **(C)(c)**. Noise accumulates as iterations increase. The sample structure cannot be resolved under 10% noise in **Fig. 9 (C)**. To deal with the effect of noise, we introduced a low-pass filter that cuts information on high frequency more than the cutoff frequency of optics. The effect of the low-pass filter is shown in **Fig. 10**. **Fig. 10 (a)** shows the observed image with the noise. **Fig. 10 (b)** shows the super-resolution postprocessed image using images as shown in **Fig. 10 (a)**. Iteration numbers 100 in **Fig. 10 (b)**. **Fig. 10 (c)** shows an image with the filter in **Fig. 10 (a)**. The super-resolution image processed with images as in **Fig. 10 (c)** is shown in **Fig. 10 (d)**. In **Fig. 10 (d)**: the result with the low-pass filter and iteration numbers 100, so the sample frequency and sample peak position are resolved correctly. The structure not resolvable in **Fig. 10 (b)** is resolved using the same number of iterations as in **Fig. 10 (d)**, confirming that the low-pass filter is effective against random noise. The influence of the amount of the noise, the shape of the sample, and the iteration time on the super-resolution result will be studied in detail in future work.

5. Conclusions

When an actual application is constructed based on our proposal, analyzing the influence of errors in standing-wave illumination parameters and noises are indispensable, as we did in computer simulation.

Resolution properties of the proposed method considering experimental errors in standing-wave illumination parameters used in postprocessing were examined. The influence of errors in standing-wave pitch and phase were also studied. It settles to the wrong solution from the surrounding part of the resolving area as error became bigger. It was confirmed that the smaller the standing-wave pitch, the stronger the error tolerance.

Pitch error analysis indicated that if the standing-wave pitch is 300 nm or less and standing-wave pitch error is 5%, super-resolution beyond the Rayleigh limit can be achieved.

Phase error analysis indicated that if the standing-wave pitch is 300 nm or less and the phase difference is 30°, super-resolution can be achieved.

To analyze noise influence, we used random noise in simulation, confirming that the influence of noise accumulated in the solution as iteration time increased. Note that the effect of noise is reduced by introducing a low-pass filter to cut high-frequency information more than the cutoff frequency of optics. We confirmed that a structure not resolved without the filter can be resolved using the filter.

In future work, we plan to use the findings obtained in this study to adjust the standing-wave parameters of the experimental apparatus.

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