RESOLUTION CHARACTERISTICS OF SUPER-RESOLUTION OPTICAL INSPECTION USING STANDING WAVE ILLUMINATION

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Abstract:
Microfabricated structures such as semiconductors and MEMS keep shrinking as nanotechnology advances. Demand that measures microfabricated structures has risen. The optics and electron beam have been mainly used for that purpose, but the resolving power of the optics is limited by the Rayleigh limit and it is generally low for defects at sub-wavelength geometries, while the scanning electron microscope needs vacuum and induces contamination in measurement. In order to find a solution to these problems, we propose the novel optical inspecting method for the microfabricated structure using standing wave shift. This method is based on a super-resolution algorithm in which the inspection system's resolution exceeds the Rayleigh limit by shifting standing wave with the piezoelectric actuator. Until now, resolution which is beyond Rayleigh limit is theoretically studied and experimentally bought to realization. It is necessary to investigate the influence that various experimental error factors gives, and to reflect it in the calibration when actual application is constructed. The standing wave pitch, the standing wave initial phase, and the noise were investigated as experimental error factors. As a result, it was confirmed to be able to achieve a super-resolution beyond Rayleigh limit if the error of the standing wave pitch was about 5% under the condition that the standing wave pitch was 300 nm or less, and if the error of the initial phase was about 30 degrees under the condition that the standing wave pitch was 300 nm. The accumulation phenomenon of noises was confirmed in the investigation of the noise effect, and it was confirmed that the low-pass filter was effective as the counter measure to the influence of noise.

Keywords: Standing wave illumination, Image reconstruction, Super-resolution

1. INTRODUTION

According to the 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. One of the key areas where improvement is needed is defect detection of semiconductor wafers [2]. Defects in the wafers include random defects like killer particles, clustered defects, scratch defects and so on. These defects deteriorate electrical chip performance and process yield in the semiconductor manufacturing process. Especially, improved inspection of patterned wafers is a necessity for the next generation of semiconductors.

Optical methods and electron beams are conventionally used for 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 property. We think optical inspection has greater potential than SEM inspection for inspection because optical inspection is non-destructive and has high throughput. So, we focused our attention on optical inspection. In optical patterned wafer inspection, resolution and defect detection beyond the Rayleigh limit are now required due to the acceleration of pattern miniaturization and development of advanced semiconductor devices [4].

One of the solutions to challenges in semiconductor optical inspection is the use of shorter wavelengths, which has been studied as a countermeasure against device miniaturization. However, as the shortening of wavelength is too limited to keep up with the challenges, we have developed a super-resolution inspection technique. Namely, when a pattern is miniaturized and made dense, light reflected from the wafer becomes weak, and the captured image 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 technique combines a standing wave illumination shift method with dark-field imaging technology to deliver optimal sensitivity for critical defect detection at sub-100-nm nodes and beyond, without compromising throughput [6][7]. The standing wave illumination shift method enables the optical resolution of micro structures that the conventional method cannot achieve. Nano-scale shifts of illumination and super-resolution post-processing are keys to achieve the resolution enhancement and higher sensitivity for defect detection. A super-resolution in the two-dimensional structure has been experimentally achieved so far [8]. In this paper, indispensable investigation of what influence is brought to the super-resolution result by effect of various errors (errors concerning standing wave illumination parameters and noises included in detected optical image) for construction of an actual application, is carried out.

2. METHODOLOGY

2.1 Standing wave illumination shift and scattered light modulation

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

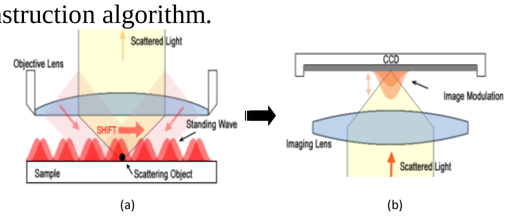

Fig. 1: Schematic diagram of the standing wave illumination shift and the scattered light modulation

2.2 Super-resolution image reconstruction algorithm for post processing

A block diagram of the super-resolution post-processing is shown in the Fig. 2. First, the sample is illuminated with standing wave illumination, and multiple images are experimentally observed by the standing wave shift. Then, calculated images are computationally obtained based on Fourier optics. The error between the observed images and the calculated images is approximately fed back to the assumed sample to obtain a reconstructed sample. The image reconstruction is iteratively calculated with successive approximation until the error converges. The nanoshifts of standing wave illumination that are modulated at about a half-wavelength scale include high-frequency spatial information, and this causes change to the scattered light images. We expect to achieve super resolution by feeding back the errors in scattered light images into sample distribution and reconstructing the sample distribution with successive approximation.

Fig. 3 shows the schematics of super-resolution. When two point samples to be observed are close enough (shown as two blue dots), the two points cannot be distinguished in the observed image. Then, the sample is illuminated by the standing wave, and multiple modulated scattered light images are obtained. These obtained images are post-processed; then the two point samples are clearly resolved as shown in the lower right image. Thus, a super resolution is achieved.

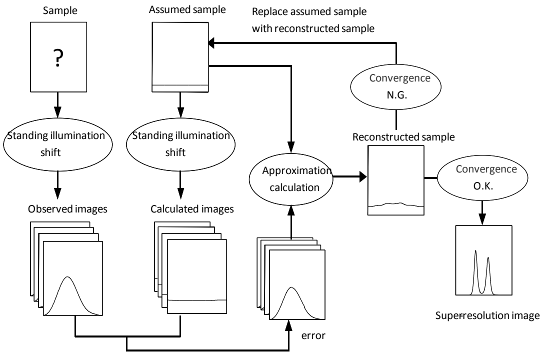

Fig. 2: Block diagram of the super-resolution post-processing

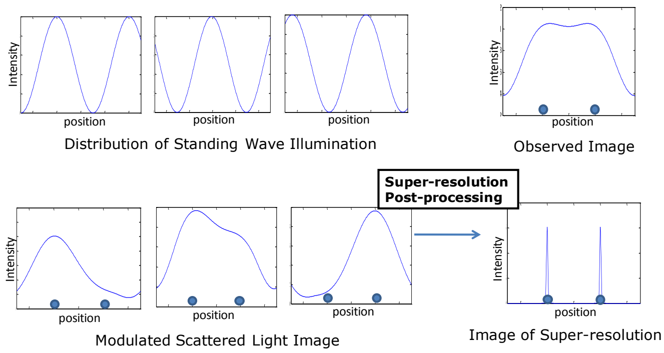

Fig. 3: The schematics of super-resolution

3. RESOLUTION CHARACTERISTICS CONSIDERING ERROR OF STANDING WAVE ILLUMINATION PARAMETERS

When a super-resolution is experimentally carried out, various error factors concerning the standing wave illumination are expected to influence the resolution result. Then, the resolution characteristics when there was an error between the values used for the super-resolution post-processing and the actual value are examined. A pitch and a phase of the standing wave illumination are taken into consideration as error factors, in this paper.

3.1 Super-resolution without error

Fig.4 shows an employed sample and a super-resolution image of sample to verify resolution characteristics considering the errors of standing wave illumination parameters. The continuous sample which is more actual than discrete sample like the sample indicated in Fig. 3 is employed. The simulation conditions are shown in Table 1.

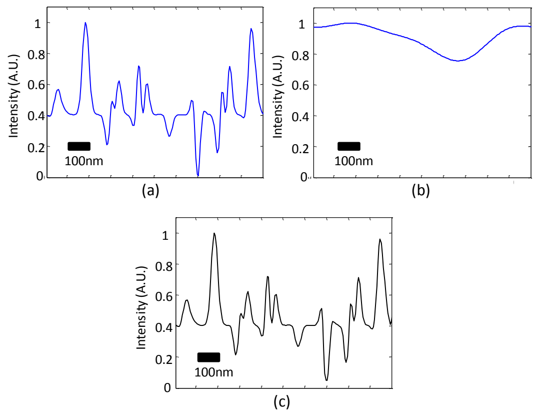

Fig. 4: Employed continuous sample (a) sample, (b) observed image by uniform illumination, (c) super-resolution image

Table 1: Conditions of simulation

Wavelength of source	488 nm
Pitch of standing wave illumination : T	300 nm
NA of objective	0.95
Rayleigh limit	313 nm
Shift times	10
Shift step size	30 nm
Iteration times	1,000,000

The employed sample (Fig. 4 (a)) is observed like Fig. 4 (b) by a normal uniform illumination. The structure of sample is not resolved in Fig. 4 (b). On the other hand, the sample structure is clearly resolved by the super-resolution image (Fig.4 (c)). The super-resolution post-processing realizes to resolve not only the discrete sample like sample indicated in Fig. 3, but also the continuous distribution like Fig. 4 (a).

3.2 Error factor: pitch of standing wave illumination

The resolution characteristics are examined, when a pitch of standing wave illumination is an error factor. The simulation conditions are basically as shown in Table.1. Fig. 5 shows the super-resolution results when there is a minute error between the standing wave pitch used by the super-resolution post-processing (300 nm) and the actual standing wave pitch. The resolution characteristics deteriorate as the error grows. The solution emanates in the surrounding part of the resolving area. It seems that an accumulating error caused by the rupture of information in the boundary of resolving area is a cause of emanation. The deterioration of resolution characteristics 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.

The resolution is quantitatively evaluated by the correlation coefficient between the sample and the super-resolution result. Fig. 6 shows the result of examining the behavior of the correlation coefficient in the conditions that the standing wave pitch is 250 nm, 300 nm, 360 nm. The smaller the standing wave pitch is, the better the resolution is. For example, the error of the standing wave pitch is about 5% under the condition of the standing wave pitch 300 nm, the super-resolution can be achieved by using the correlation coefficient at the Rayleigh limit as a resolution index.

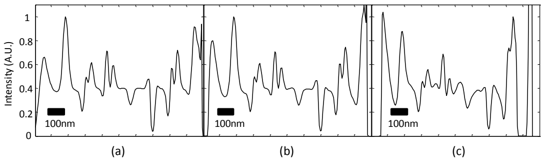

Fig. 5: Super-resolution post-processed images obtained using pitch 300 nm (a) actual pitch 302 nm, (b) actual pitch 305 nm, (c) actual pitch 315 nm

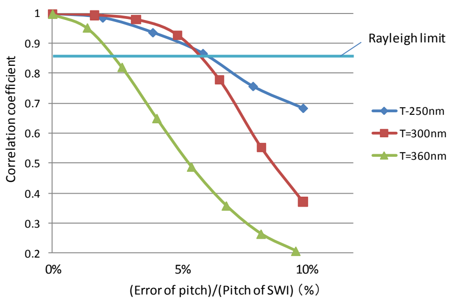

Fig. 6: Behaviour of correlation coefficient with mismatch of pitch of standing wave illumination

3.3 Error factor: phase of standing wave illumination

The resolution characteristics when a phase of standing wave illumination is an error factor are also examined. The simulation conditions are basically as shown in Table.1. Fig. 7 shows super-resolution results when there is difference between the phase of standing wave used by the super-resolution post-processing and the actual phase of standing wave. A similar tendency is seen between Fig. 5 and Fig. 7.

The quantitative evaluation is carried out by the correlation coefficient. Fig. 8 shows the result of examining the behavior of the correlation coefficient in the conditions that the standing wave pitch is 250 nm, 300 nm, 360 nm, 420 nm. The smaller the standing wave pitch is, the better the resolution is. The resolution characteristics depend on the standing wave pitch. For example, the phase difference is about 30 degrees under the condition of standing wave pitch 300 nm, the super-resolution can be achieved by using the correlation coefficient at the Rayleigh limit as a resolution index.

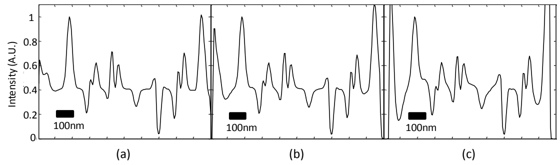

Fig. 7: Super-resolution post-processed images with phase difference (a) 2 degrees, (b) 6 degrees, (c) 18 degrees

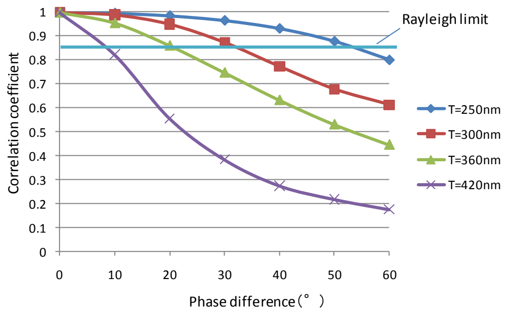

Fig. 8: Behaviour of correlation coefficient with phase difference of standing wave illumination

4. RESOLUTION CHARACTERISTICS CONSIDERING NOISE

The influence that the noise brought to the resolution characteristics is investigated. And a low-pass filter is introduced as a counter measure to the effect of noise. As the first step, a random noise which contains all frequencies is put on observed image with an optical system. The results of investigation are shown in Fig. 9 and Fig. 10. Fig. 9 shows the appearance where the noise accumulates. Fig. 9 (A) shows an employed periodical sample (150 nm pitch). Observed images of the sample with the standing wave illumination are shown in Fig. 9 (B). Fig. 9 (B)(a) shows observed image without a noise. The image that 10% random noise is added to Fig. 9 (B)(a) is Fig. 9 (B)(b). The super-resolution post-processing was carried out with the random noise added images like Fig. 9 (B)(b). Fig. 9 (C) shows super-resolution post-processed images. Each iteration times of Fig. 9 (C)(a), (C)(b), (C)(c) are 10, 100, 1000. The noise accumulates as the iteration time increases. The sample structure cannot be resolved under the condition of 10% noise in Fig. 9 (C). To deal with the effect of noise, the filter was introduced. It is a low-pass filter that cuts information on the high frequency more than the cutoff frequency of the optical system. 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 post-processed image using images like Fig. 10 (a). The iteration time is 100 in Fig. 10 (b). Fig. 10 (c) shows the image that is put the filter on Fig. 10 (a). The super-resolution image that processed with images like Fig. 10 (c) is shown in Fig. 10 (d). In Fig. 10 (d): the result with the low-pass filter and the iteration time 100, frequency of the sample and position of the sample peak are correctly resolved. The structure which cannot be resolved in Fig. 10 (b) is resolved by the same iteration time in Fig. 10 (d). It is confirmed that the low-pass filter is effective to the 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 investigated in detail in future.

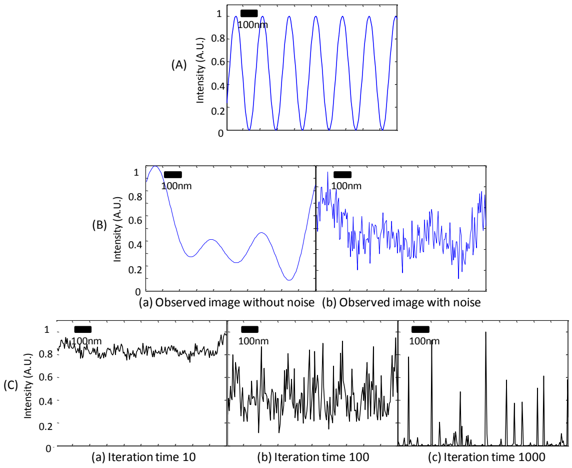

Fig. 9: Accumulation of noise (A) sample, (B) observed images with standing wave, (C) super-resolution post-processed images without filter,

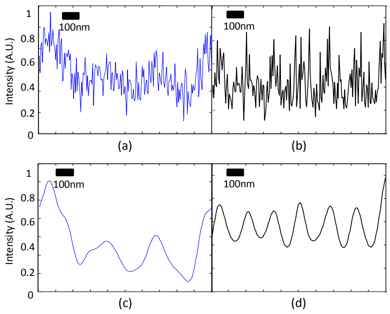

Fig. 10: Effect of low-pass filter, (a) observed image with noise, (b) super-resolution post-processed image without filter, (c) filtered image on (b), (d) super-resolution post-processed image without filter

5. CONCLUSION

When an actual application is constructed based on the proposal method, analyzing the influence of errors of standing wave illumination parameters, and noises are indispensable. So, we investigate the influence with the computer simulation.

The resolution characteristics of the proposed method considering experimental errors of the standing wave illumination parameters used in the post-processing were examined. The influence of errors of the standing wave pitch and phase are investigated. The solution emanated from the surrounding part of the resolving area as the error grew. And it was confirmed that the smaller the standing wave pitch was, the stronger the tolerance to the error was.

By the pitch error analysis, it was indicated if the standing wave pitch is 300 nm or less and the error of the standing wave pitch is about 5%, the super-resolution beyond Rayleigh limit can be achieved.

By the phase error analysis, it was indicated if the standing wave pitch is 300 nm or less and the phase difference is about 30 degrees, the super-resolution can be achieved.

To analyze the influence of noises, the random noise was used and simulation was carried out. It was confirmed that the influence of the noise was accumulated in the solution as the iteration time increased. It can be seen that the cumulation effect of the noise is reduced by introducing the low-pass filter that cut the high frequency information more than the cutoff frequency of the optical system. It was confirmed that the structure cannot be resolved without the filter became possible to resolve by the filter introduction.

In the future work, the finding obtained by this study will be used for the adjustment of the standing wave parameter of the experimental apparatus.

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