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Research Article

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Lateral resolution improvement of laser-scanning imaging for nano defects detection

Abstract: Demand for higher efficiency in the semiconductor manufacturing industry is continually increasing. In particular, nano defects measurement on patterned or bare Si semiconductor wafer surfaces is an important quality control factor for realizing high productivity and reliability of semiconductor device fabrication. Optical methods and electron beam methods are conventionally used for the inspection of semiconductor wafers. Because they are nondestructive and suitable for high-throughput inspection, optical methods are preferable to electron beam methods such as scanning electron microscopy, transmission electron microscopy, and so on. However, optical methods generally have an essential disadvantage about lateral spatial resolution than electron beam methods, because of the diffraction limit depending on the optical wavelength. In this research, we aim to develop a novel laser-scanning imaging method that can be applied to nano-/micro manufacturing processes such as semiconductor wafer surface inspection to allow lateral spatial super-resolution imaging with resolution beyond the diffraction limit. In our proposed method, instead of detecting the light intensity value from the beam spot on the inspection surface, the light intensity distribution, which is formed with infinity corrected optical system, coming from the beam spot on the inspection surface is detected. In addition, nano scale shifts in the beam spot are applied for laser spot scanning using a conventional laser-scanning method in which the spots are shifted at about a 100 nm pitch. By detecting multiple light intensity distributions due to the nano scale shifts, a super-resolution image reconstruction with resolution beyond the diffraction limit can be expected. In order to verify the feasibility of the proposed method, several numerical simulations were carried out.

Keywords: Gaussian spot illumination; image reconstruction; optical inspection; optical measurement; super-resolution.

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1 Introduction

The miniaturization of semiconductors is progressing as nanotechnology advances, and according to the International Technology Roadmap for Semiconductors (ITRS) roadmap [1], a next-generation defect inspection system capable of sub-100 nm inspection for semiconductors is urgently demanded. Currently, optical methods [2, 3] and electron beam methods are conventionally used for semiconductor wafer inspection. From the viewpoint of their non-destructiveness and high-throughput characteristics, optical methods are preferable to electron beam methods such as scanning electron microscopy, transmission electron microscopy, and so on. However, optical methods generally have essential disadvantages regarding lateral spatial resolution. Its lateral resolution is restricted by the diffraction limit depending on the optical wavelength.

One of the solutions to overcome the diffraction limit is super-resolution inspection using structured illumination [4, 5]. Using standing wave illumination (SWI), which can be generated based on interference phenomena, as a structured illumination, it is confirmed that minute structure under diffraction limits can be resolved [6]. In super-resolution inspection using SWI, the fineness of each peak of the SWI directly determines its performance.

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It is true that SWI can illuminate a wide range, and high-throughput can be achieved. However, it is difficult to directly apply super-resolution inspection based on SWI to practical inspection methods during the manufacturing process, because the optical system necessary to form the SWI is rather complex. Furthermore, the pitch of the SWI, which is an important factor affecting the proper super-resolution post-processing, can easily vary due to disturbances such as vibration in the manufacturing environment, since interference phenomena are particularly vulnerable to such problems.

Therefore, fine structured illumination that is robust to vibration is strongly required. In this research, as the first step in the study of fine structured illumination meeting this requirement, we examine the application of Gaussian spot illumination (GSI), the fine size of which is equivalent to that of SWI. However, GSI can be formed without complex optics using interference phenomena, and it only requires a simple optical focusing unit.

In this paper, we tried to confirm the feasibility of GSI as structured illumination from theoretical and numerical viewpoints, and its basic super-resolution characteristics were numerically analyzed. In addition to the super-resolution application, we also studied the applicability to highly sensitive detection of nano particulates on mirrored surfaces with micro roughness.

2 Methodology

Figure 1 shows the concept of our proposed method compared with confocal laser scanning microscopy (CLSM) [7, 8]. In our proposed method, instead of detecting the light intensity value coming from the beam spot on the inspection surface, as in CLSM, the light intensity distribution, which is formed with infinity corrected optical system, coming from beam spot on the inspection surface is detected (Figure 1). In addition, nano scale shifts by distances much smaller than the beam spot are applied for laser spot scanning, whereas in conventional CLSM the shift distances are about the size of the beam spot. By detecting multiple light intensity distributions obtained with the nano scale shifts, super-resolution image reconstruction beyond the diffraction limit can be expected.

A schematic diagram of the variation in an imaging distribution due to a small spot shift is shown in Figure 2. Here, the beam spot shift is on the nanometer scale. Because the distribution of the beam spot is not uniform, but has Gaussian shape, the observed imaging distributions are modulated as the position of the beam spot shifts laterally. With this method, multiple images modulated by the spot shifts can be detected.

Next, super-resolution image reconstruction is accomplished by post-processing [5] of the multiple images from the GSI shifts. A basic block diagram of the super-resolution post-processing is shown in Figure 3. First, the sample is illuminated with GSI, and multiple images are experimentally observed by shifting the GSI. On the other hand, initially we set the assumed sample having uniform value. And we numerically calculate its optical image under these experimental conditions based on Fourier optics. Then, a reconstructed image is obtained by approximately feeding back the errors between the experimentally observed images and the computationally calculated images to the initial assumed sample. The initial assumed sample is replaced with a reconstructed image, which is iteratively

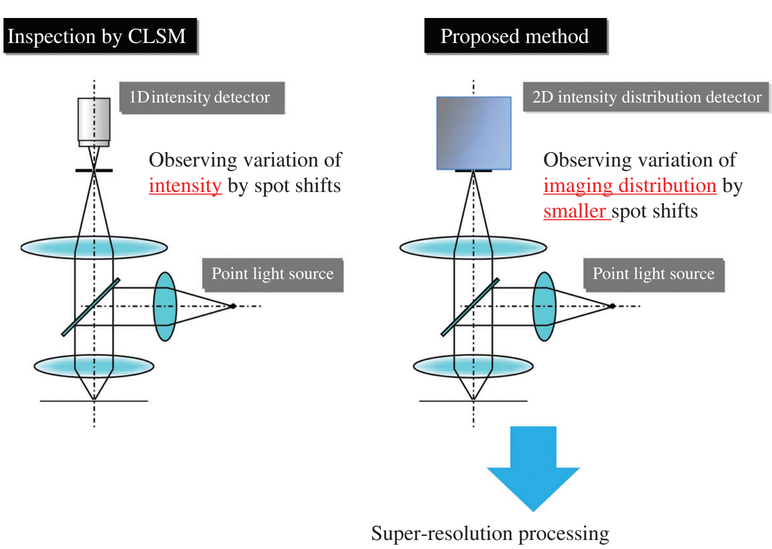

Figure 1 Schematic comparison between CLSM and the proposed method.

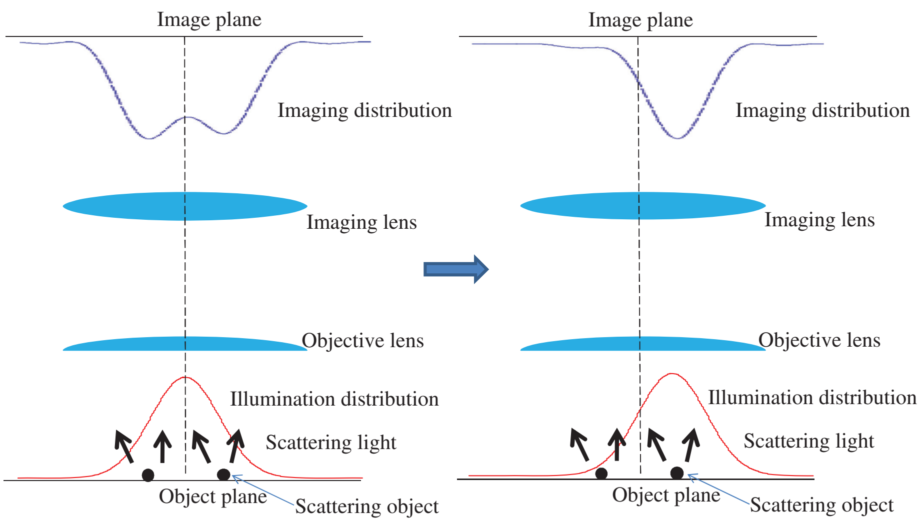

Figure 2 Schematic diagram of the variation in the imaging distribution due to a smaller spot shift.

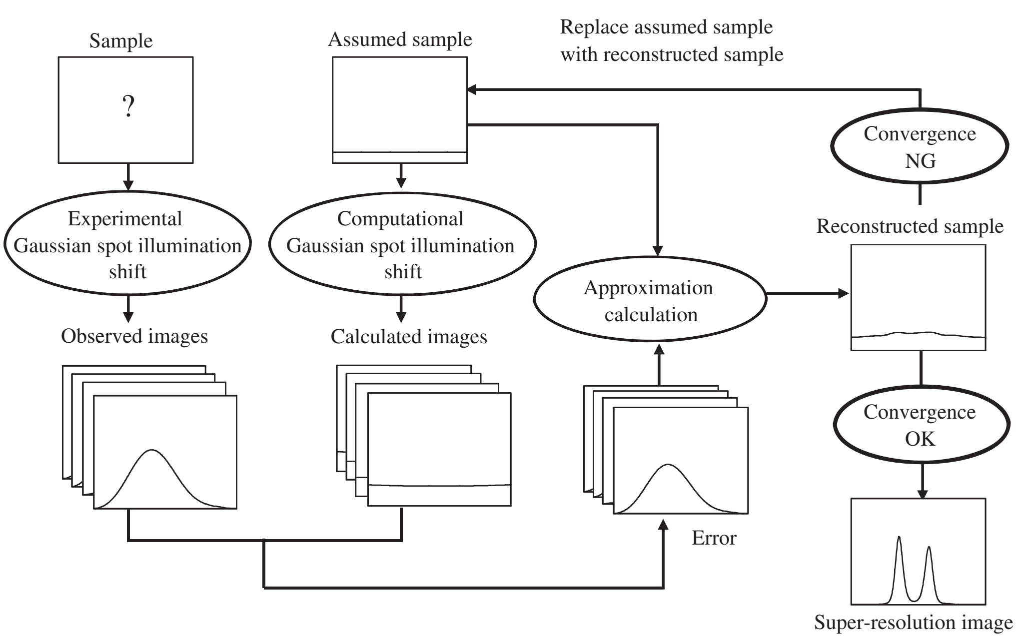

Figure 3 Basic block diagram of the super-resolution post-processing [5].

calculated with successive approximations until the error converges. In this manner, super-resolution inspection with resolution beyond the diffraction limit can be expected [5].

3 Simulation

3.1 Super-resolution simulation for a point-sample

First, in order to analyze the basic characteristics of the image reconstruction of the proposed method, several numerical simulations were performed using a point-sample and were compared with the results obtained using conventional microscopy.

Table 1 shows the parameters used for the simulation. Figure 4A shows a sample with an ideal impulse shape, and Figure 4B is the image obtained using conventional microscopy. The scale on the horizontal axis corresponds to a size on the object plane. It can be said that obtained image is broadened because of diffraction.

On the other hand, Figure 4C shows the multiple imaging distributions obtained by very small shifts (30 nm) of the beam spot of GSI (the diameter of which is 300 nm).

Table 1 Simulation setup.

Wavelength of light source: λ	488 nm
Spot diameter: D	300 nm
Numerical aperture of imaging optics: NA	0.9
Rayleigh diffraction limit: L	330 nm
Shift step: S_s	30 nm
Shift count: T_s	30
Iteration count: I_c	10 000
Size of CCD (charge-coupled device) pixel: C	8.3 µm
Magnification power: MP	1000

As shown in Figure 4C, indeed each image is still affected by diffraction, but the observed image varies with the GSI shifts. The result after super-resolution post-processing is shown in Figure 4D. While the half-width in conventional microscopy is 278.8 nm, that of the proposed method is 14.4 nm. This suggests that the broadened optical image obtained from a point-sample, which corresponds to the impulse response, can be narrowed beyond the diffraction limit by image reconstruction using the proposed method.

3.2 Super-resolution simulation for two discrete samples

Second, in order to understand the basic characteristics of the resolution power of the proposed method clearly, several numerical simulations were performed using two discrete samples, under the same conditions used in Section 3.1, except for I_C.

We investigated whether two discrete samples separated by distances of 300 nm, which is near the Rayleigh limit, and <100 nm were resolved. Figure 5A shows a sample distribution with 300 nm distance and conventional microscopic image. Figure 5B is the reconstructed image. From Figure 5, it can be seen that samples that have the distance near the Rayleigh limit can be discretely resolved using the proposed method.

Figure 6A shows a sample distribution with 80 nm distance and conventional microscopic image. Figure 6B shows the reconstructed images after (a) 0, (b) 200, (c) 2000, and (d) 10 000 iterations. Here, the 0th iteration means the initial assumed sample. We confirmed that a spatial resolution of 80 nm could be achieved when the Rayleigh limit is 330 nm.

4 Characteristics of lateral resolution improvement

As the first step, in order to analyze the characteristics of the lateral resolution improvement, we investigated the

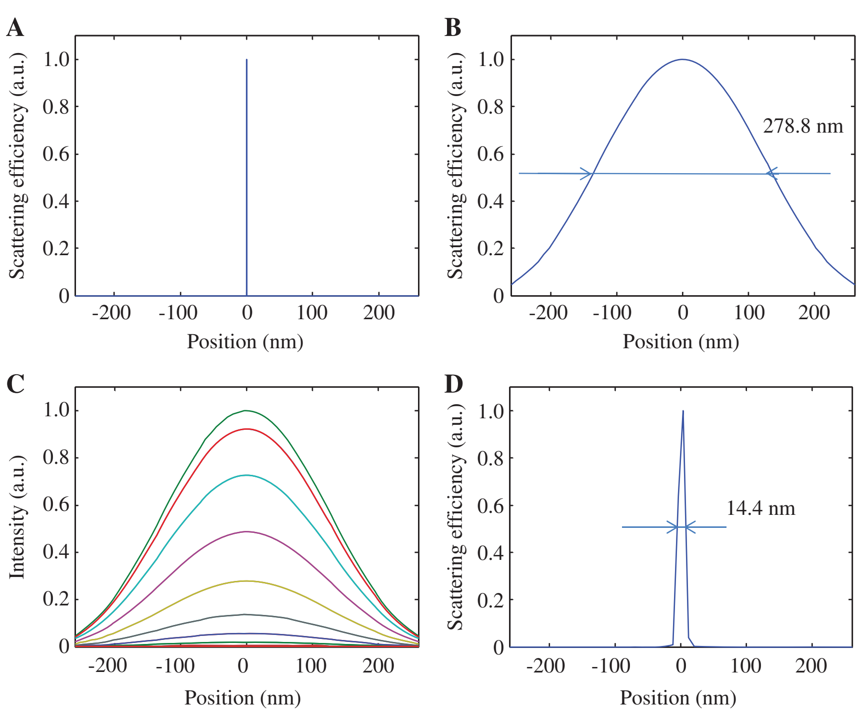

Figure 4 Super-resolution simulation of a point-sample.
(A) Sample distribution. (B) Image obtained by conventional microscopy. (C) Images obtained by multiple GSI shifts. (D) Reconstructed image after super-resolution post-processing.

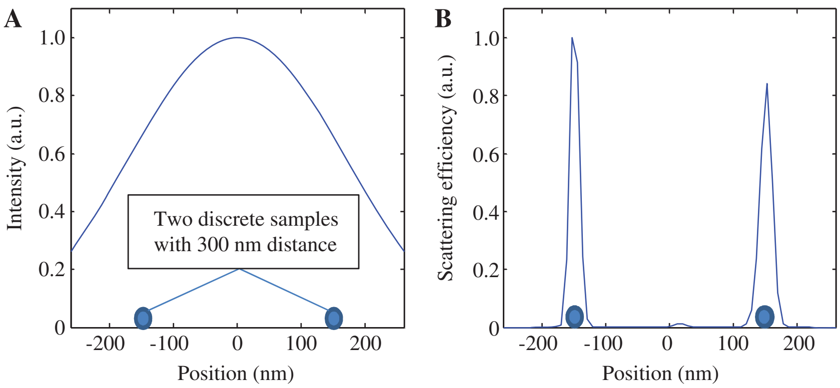

Figure 5 Super-resolution simulation of two discrete samples with 300 nm distance. (A) Conventional microscopic image. (B) Reconstructed image.

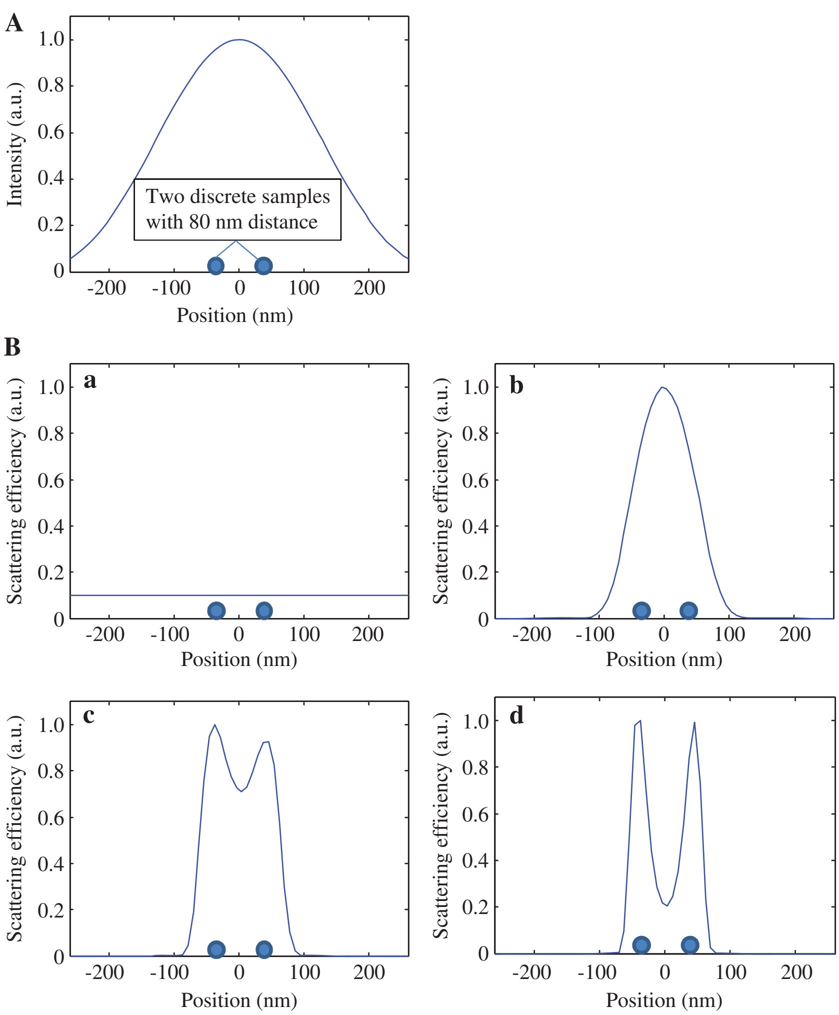

Figure 6 Super-resolution simulation of two discrete samples with 80 nm distance. (A) Conventional microscopic image. (B) Reconstructed image during super-resolution post-processing with (a) 0, (b) 200, (c) 2000, and (d) 10 000 iterations.

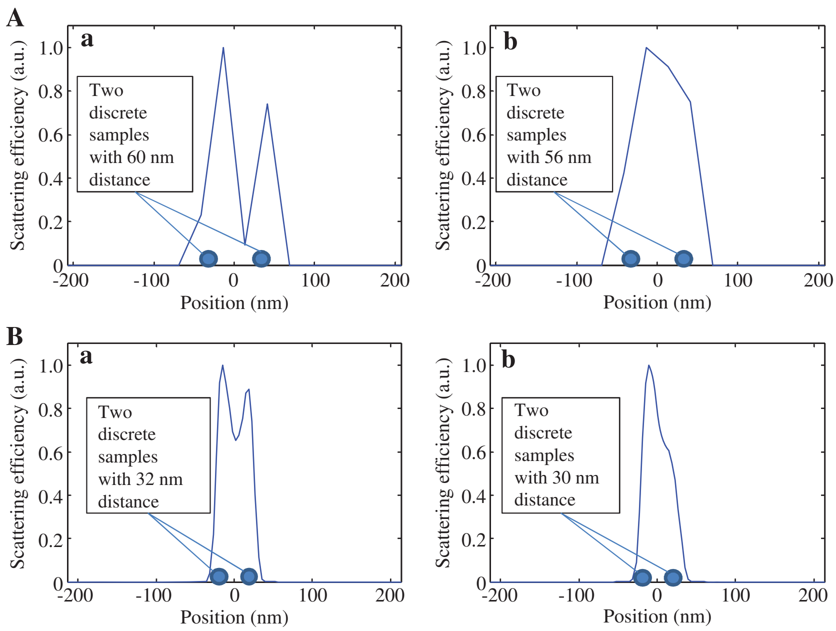

Figure 7 Typical results for the relationship between lateral resolution and MP (magnification power). MP: (A) 300, distance of samples: (a) 60 nm, (b) 56 nm. (B) 2000, distance of samples: (a) 32 nm, (b) 30 nm.

relationship between the lateral resolution and magnification power (MP) of the optical system, which is one of the most significant parameters for practical use. Figure 7A and B show the typical reconstructed images used as examples of the variation in MP. According to Figure 7, the lateral resolution directly depends on the MP and seems to improve with increasing MP.

Figure 8 shows the relationship between MP and the lateral resolution under the following typical imaging conditions: λ=488 nm, D=300 nm, NA=0.95, S_S=40 nm, S_C=50, I_C=400 000, and C=8.3 µm. Here, we estimated whether samples were resolved or not based on the Rayleigh limit. That is, we consider the resolution to have been successful if the ratio of the mean intensity of the two peaks and the intensity of the valley between them is more than the ratio defined in the Rayleigh limit. Table 2 shows the relationship between the MP and the sampling size, which is determined by the resolving power of the CCD imaging sensor. Specifically, the sampling size is twice the distance that 1 pixel of CCD covers on the object plane.

According to Figure 8, until the MP is 500, the lateral resolution improves with increasing MP and is directly restricted by the sampling size. However, when the MP becomes more than 1000, very little further improvement in the lateral resolution is observed, and the lateral resolution approaches about 30 nm asymptotically regardless of the sampling size. This suggests that this asymptotic value

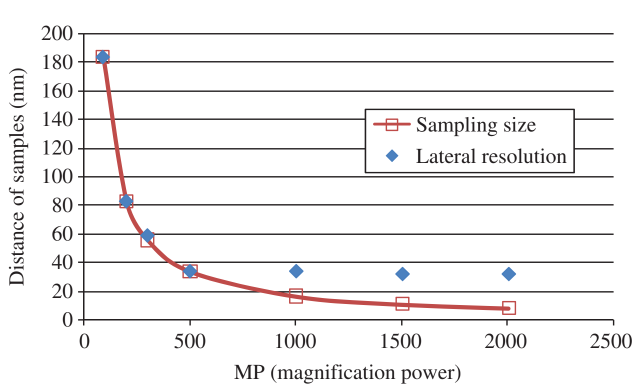

Figure 8 Relationship between lateral resolution and MP.

Table 2 Relationship between MP and sampling size.

MP (magnification power)	Sampling size (nm)
90	184
200	83
300	56
500	34
1000	16.6
1500	11
2000	8.4

is not restricted by the sampling size, but seems to depend on the other imaging conditions such as the *NA*, spot size, step size, and so on. Indeed, it will be important to discuss the quantitative relationships between this asymptotic value and the other parameters, but, from this result, we can see that an excess magnification of the optical system would be meaningless, and a magnification of about 500 is sufficient under the typical practical condition.

5 Applicability to nano particulate detection on a bare Si wafer surface

In addition to the improvement in lateral resolution, the proposed method could also improve the sensitivity for nano particulate detection on a mirrored surface, which is required for the inspection of bare semiconductor Si wafer surfaces. In general, detection of nano particulates on the wafer surface is difficult for minuteness of the particulates because the signal from the particulate can be buried among the noise from the micro roughness. Therefore, in this section, we tried to verify the applicability of the proposed method to nano particulate detection on a bare wafer surface by performing numerical simulations with noise values corresponding to micro roughness of the surface. The simulation conditions are as follows: λ=488 nm, D=300 nm, NA=0.95, S_S=40 nm, S_C=50, I_C=400 000, and C=8.3 µm.

Figure 9A shows a point-sample with random noise, corresponding to a single nano particulate with the micro roughness of the surface. The noise level was set to 10% of the original sample intensity. Figure 9B shows the conventional microscopic image, in which the peak of the signal from the point-sample can be seen in the central part, and the signal-to-noise (SN) ratio is low. The ratio of the peak intensity to that of the next strongest peak is 1.05. Thus, it can be said that it is difficult to detect the particulate against the background noise. Figure 9C is the image distribution under the condition that a point-sample and the peak of the spot illumination are placed at the same position, and Figure 9D shows the multiple imaging distributions obtained by spot shifts. The envelope shows a similar tendency to that in Figure 9B, and the ratio of the peak intensity to that of the next strongest peak is 1.12. It is easier to distinguish the signal from a point-sample in this image than in the conventional microscopic image, but it is still difficult to definitively detect a particulate.

The result after super-resolution post-processing is shown in Figure 10. The signal in the central part is clearly stronger than the background noise. The ratio of the peak

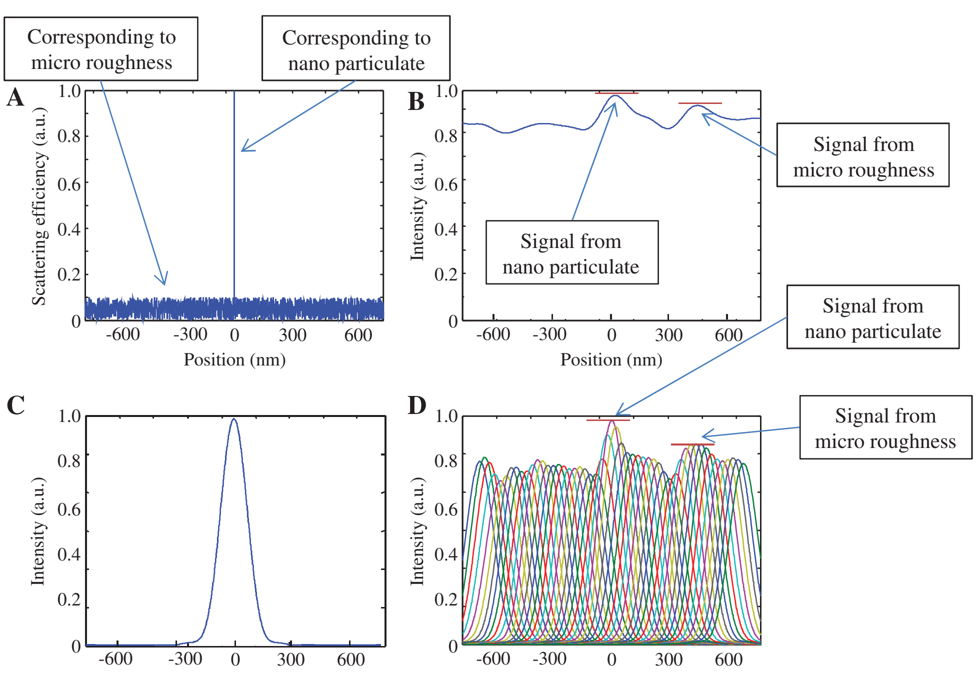

Figure 9 Simulation image with noise.
(A) Sample distribution with noise. (B) Image obtained by conventional microscopy. (C) Image obtained by GSI. (D) Image obtained with multiple GSI shifts.

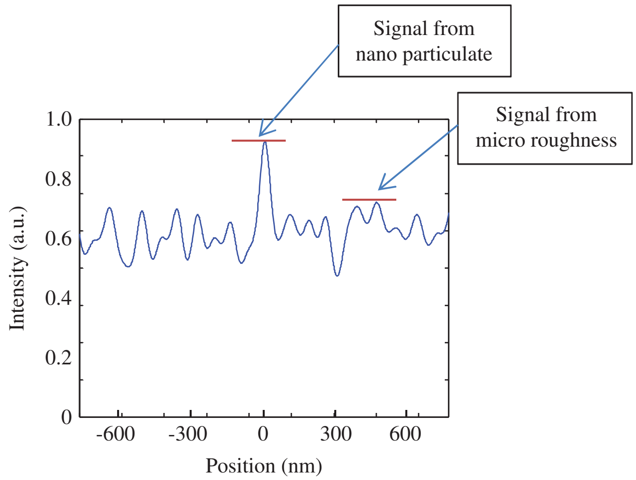

Figure 10 Reconstructed image after super-resolution post-processing.

intensity to that of the next strongest peak is 1.28. The SN ratio is improved, and it is easier to detect the signal from a discrete sample than in the conventional microscopic image or in the image obtained from the spot shifts. From these results, we can see the sensitivity improvement (increase in SN) and the applicability of the proposed method to nano particulate detection on a bare wafer surface.

6 Conclusions

In this paper, we proposed a novel laser-scanning imaging method that can be applied to nano-/micro manufacturing processes to allow lateral spatial super-resolution imaging with a resolution beyond the diffraction limit. Numerical simulations for a point-sample show that the broadened optical image obtained from a point-sample, which corresponds to the impulse response, can be narrowed beyond the diffraction limit by image reconstruction using the proposed method. In the case of two discrete point-samples, we confirmed that the proposed method could achieve sub-100 nm super-resolution when the Rayleigh limit is 330 nm. According to the detailed analysis of the dependence of the lateral resolution improvement on the magnification power of the imaging optics, the resolving power directly depends on the lateral sampling size, which is defined as the size of the area 1 pixel of the image device (CCD) covers on the object plane. A magnification larger than 500 (for a lateral sampling size of 30 nm) is needed to achieve the best performance.

In addition to the improvement in the lateral resolution, we also confirmed that the proposed method can improve the sensitivity of nano particulate detection on a mirrored surface with micro roughness. For future work, we will analyze the relationship between measurement time and proper super-resolution condition, and the essential physical resolution power of the proposed method by performing verification experiments.

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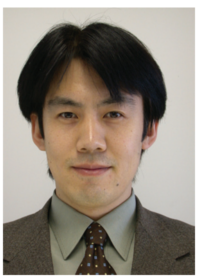

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