Resolving Power Improvement for Optical Nano-Defect Measurement by using Sub-Pixel Sampling based on Structured Illumination Shift Method

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KEYWORDS : Nano-Defect Measurement, Resolving Power Improvement, Optical Imaging, Sub-Pixel Sampling, Structured Illumination

Resolving power improvement is strongly required in various optical measurements. Especially, optical defect inspection on next-generation semiconductor wafer needs higher resolving power without compromising measurement speed. That is because semiconductor design rules continue to shrink up to less than 100nm and inspection area on a wafer surface has been wider up to more than 300mm. Resolving power in optical imaging is limited not only by optical diffraction but also by sampling size determined by magnification of optics and pixel size of imaging device such as CCD or CMOS. One of the solutions to improve the resolving power in the optical imaging is use of a shorter wavelength and miniaturization of pixel size of the imaging device. However, wavelength and pixel size used in imaging cannot keep up with the shrinking design rules of the semiconductor devices. So, we have proposed an optical resolving power improvement method using structured illumination shift. This proposed method is based on the active control of spatial distribution of structured light illumination and iterative reconstruction of multiple images in image processing. And we have developed a novel optical measurement system including specific properties such as non-destructiveness, high resolving power and high throughput, which are strongly required in semiconductor wafer inspection. As a result of theoretical and experimental verifications, the proposed method has more resolving power beyond the optical diffraction limit extended by the structured light illumination with the successive approximation acting as the extrapolation effect. On the other hand, a problem still remains, that resolving power is limited also by sampling interval determined by magnification of optics and pixel size of imaging device. This problem is related to measurement speed. The smaller sampling interval causes the lower speed of the optical measurement, because visual field of imaging optics is determined by size and number of a CCD pixel. In order to find a solution to this problem, we focused attention on sub-pixel sampling with structured illumination shift method. Sub-pixel image-processing is a method to improve the resolving power without narrowing the visual field of imaging optics. And it is expected that the structured illumination shift method provide a sub-pixel resolving power without mechanical displacement of a CCD camera We investigated a relationship between CCD pixel size and resolving power provided by structured illumination shift method. And it was found, that sub-pixel spatial shift of structured illumination provides not only optical resolving power improvement but also sub-pixel sampling for optical imaging.

Manuscript received: July 15, 2009 / Accepted: August 15, 2009

NOMENCLATURE

CCD = Charge Coupled Device
CMOS = Complementary Metal Oxide Semiconductor
ITRS = International Technology Roadmap for Semiconductors
PSF = Point Spread Function
OTF = Optical Transfer Function
MTF = Modulation Transfer Function

1. Introduction

Defect review inspection on a new generation semiconductor wafer needs higher resolving power without compromising throughput. According to the ITRS roadmap [1], non-destructive and production worthy wafer microscopy for critical dimension measurement for defect detection and analysis, is required. Difficulties of defect-detection challenge are increasing exponentially with shrinking design rules [2].

Optical methods and electron beams are conventionally used for semiconductor wafer inspection [3]. However, the inability of the optical inspection to handle the continuous miniaturization of interconnects has become a major issue, because resolving power of optical method is limited to wavelength scale by diffraction. The inspection method with electron beam has nano-scale resolving power, but it is destructive method ,and also not useful for wide-area inspection because of its low throughput properties.

We focused attention on the optical measurement method because it is nondestructive, and has high throughput properties and potential for higher resolving power of sub-wavelength scale. In optical defect review, resolving power beyond the diffraction limit is now required due to accelerating pattern miniaturization and the development of advanced semiconductor devices. One of the solutions to challenges is the use of a shorter wavelength, which has been studied as a possible countermeasure against device miniaturization. However, the shortening of wavelength cannot keep up with the challenges and has a limit, so we have proposed a novel optical measurement technique with higher resolving power than conventional methods. The proposed technique combines the structured illumination microscopy [4][5] with spatial shift of illumination and multiple image reconstruction to deliver optimal sensitivity and higher signal-to-noise ratio for critical defect review at sub-wavelength scale.

The structured illumination shift method enables the inspection optics to resolve patterns that the conventional method cannot. Nano-scale spatial shift of structured illumination and obtaining multiple images with respect to each spatial position of the structured illumination are keys to achieving resolving power improvement and higher sensitivity for defect detection.

We have developed a novel optical measurement system including specific properties such as non-destructiveness, high resolving power and high throughput. As a result of theoretical and experimental verifications, the proposed method has more resolving power beyond the optical diffraction limit extended by the structured light illumination with the successive approximation acting as the extrapolation effect[6].

However, resolving power of optical imaging system is limited not only by the diffraction but also by spatial sampling determined by magnification of optics and pixel size of imaging device. This problem is related to measurement throughput. The smaller sampling interval causes the lower speed of the optical measurement, because visual field of imaging optics is determined by size and number of a CCD pixel. In order to find a solution to this problem, we have got an idea of sub-pixel sampling with structured illumination shift method. Sub-pixel image-processing is a method to improve the resolving power determined by spatial sampling without narrowing the visual field of the imaging optics. And it is expected that sub-pixel spatial shift of structured illumination provide optimal resolving power without mechanical moving of imaging optics like a CCD camera.

2. Resolving Power Improvement Using Structured Illumination

2.1 Basic Principle of Resolving Power Improvement

An optical imaging system is generally shift-invariant, so an image can be represented by convolution of a scattered light signal and a point spread function. The scattered light image $r(x)$ is determined from the specimen distribution $a(x)$ and the illumination intensity distribution $i(x)$ by the following equation.

$$r(x) = PSF(x) \otimes (a(x) \cdot i(x)) \tag{1}$$

In this equation, $PSF(x)$ is a point-spread function of the imaging optics, which represents the airy disk image by the diffraction and $\otimes$ is a convolution operator. The scattered light image $r(x)$ is modulated by shifting the structured illumination intensity $i(x)$ into different positions.

In the structured illumination shift method, the concept of the method is shown in the Fig. 1, one of the resolving power improvement factors is a spectrum extension of the observed optical system by the spatial distribution of structured illumination. The spatial distribution $i(x)$ can be expressed as

$$i(x) = \frac{1+\cos(2\pi f_m x + \phi)}{2} \tag{2}$$

, where f_m is the spatial frequency of the structured illumination and ϕ is the phase of the structured illumination. From equations (1) and (2), we can find

$$R(f) = \frac{1}{2}OTF(f)A(f) + \frac{1}{4}e^{i\phi}OTF(f)A(f-f_m) + \frac{1}{4}e^{-i\phi}OTF(f)A(f+f_m) \tag{3}$$

, where R(f) is the Fourier transform of the image with structured illumination r(x), OTF is the optical transfer function and A(f) is the Fourier transform of the specimen distribution. The first term of equation (3) means that the spatial frequency of r(x) is restricted by the cutoff frequency f_c depending on the OTF, which is the same as in a conventional image with uniform illumination. And the second and third terms of this equation mean that the spatial frequency of r(x) is expanded to the spatial frequency of the structured illumination ($f_c \pm f_m$). Then, we obtain the resolving power with structured illumination. Based on the Rayleigh criterion, the resolving power improved by the effectiveness of the high frequency components of the structured illumination can be expressed as follows.

$$\text{Resolving Power with Structured Illumination} = \frac{1.22}{f_c + f_m} \tag{4}$$

$$\left(\text{Diffraction Limited Imaging} : \frac{1.22}{f_c}\right)$$

This means that the resolving power depends on the spatial distribution of structured illumination as well as the imaging optics.

Moreover, we found that the structured illumination shift method has the possibility to obtain extra high resolving power by using successive approximation acting as the extrapolation effect mentioned in the next section.

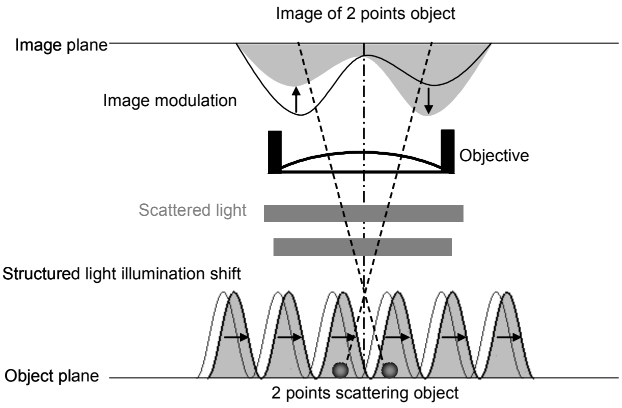

Fig. 1 Schematic diagram of the structured illumination shift and the scattered light image modulation

2.2 Reconstruction of Multiple images

In order to use spatial information from the structured illumination in carrying out the calculation, we constructed a multiple image reconstruction algorithm including iterative operations [6].

The equation (1) is discretely described as

$$r_i = \sum_{j=1}^{N} psf_{|i-j|}\, i_j a_j \quad (1 \le i \le N) \tag{5}$$

, where r_i, $psf_{|i-j|}$, i_j, and a_j are the image distribution, the PSF, the illumination intensity distribution, and the specimen distribution, respectively. Suffix i represents a discrete position in the image plane and j represents that in the object plane. The equation (5) can be simply described using a coefficient matrix as

$$R = KA \tag{6}$$

, where A is the specimen distribution matrix, R is the image matrix, and K is a coefficient matrix of imaging determined by the

PSF and the illumination intensity. The A is converted into R with K, so the imaging is represented by a linear simultaneous equation.

The resolving power improvement is realized by solving equation (6) for A, but a mathematical condition of the linear simultaneous equation of optical imaging is generally bad for calculation. Especially under actual conditions such as those with high levels of noise, convergence is difficult in the resolving calculation.

In order to solve this equation, we constructed an iterative image reconstruction algorithm in which one of the multiple images is occasionally used in the reconstruction and an assumed solution is then reconstructed. The block diagram of this algorithm is shown in Fig. 2 and the steps of the procedure are as follows.

Step 1: A specimen is assumed to be a scattering factor distribution. The initial value of the assumed specimen is a constant value A_0. And the assumed specimen is illuminated with the structured illumination which is computationally calculated. The initial calculated multiple images R_{Sm} are given, where m is the iteration number.

Step 2: An actual image of the specimen with structured illumination is observed by an experiment. The observed multiple images R_{Em} are obtained by the diffraction-limited imaging optics.

Step 3: The differences between the calculated and observed images are given as an error ratio with respect to each elements of image matrix. The error ratio E_{m} is as

$$E_{\mathrm{m}}(i) = \frac{R_{\mathrm{Em}}(i) - R_{\mathrm{Sm}}(i)}{R_{\mathrm{Sm}}(i)} \tag{7}$$

, where i represents an element of matrix (row number i).

Step 4: The error ratio E_{m} is fed back to the assumed specimen. The assumed specimen is reconstructed with the coefficient matrix K. A partition matrix to reconstruct the assumed specimen A_{m} can be calculated with respect to each element of error ratio as following equation.

$$\begin{aligned} a_{\mathrm{m}+1}(i) &= a_{\mathrm{m}}(i) + w(i)\cdot e_{\mathrm{m}}(i)\cdot a_{\mathrm{m}}(i) \\ w(i) &= \frac{k(i,i)}{\sum_{j=1}^{N} k(i,j)}, \quad k(i,j) = psf(|i-j|)\cdot i(j) \end{aligned} \tag{8}$$

, where $a_{\mathrm{m}}(i)$ is the element of A_{m}, $w(i)$ is the weighting coefficient element $e_{\mathrm{m}}(i)$ is the element of error ratio, and $k(i, j)$ is the element of the coefficient matrix K.

Step 5: The assumed specimen A_{m} (initially A_0) is replaced by the reconstructed specimen $A_{\mathrm{m}+1}$. The reconstructions are applied to the other shifted position of the standing wave illumination.

Step 6: The reconstruction steps 1-5 is iteratively applied to decrease the error ratio and to converge the solution.

By using the reconstruction method described above, the assumed specimen approaches the object distribution of the actual specimen to improve resolving power.

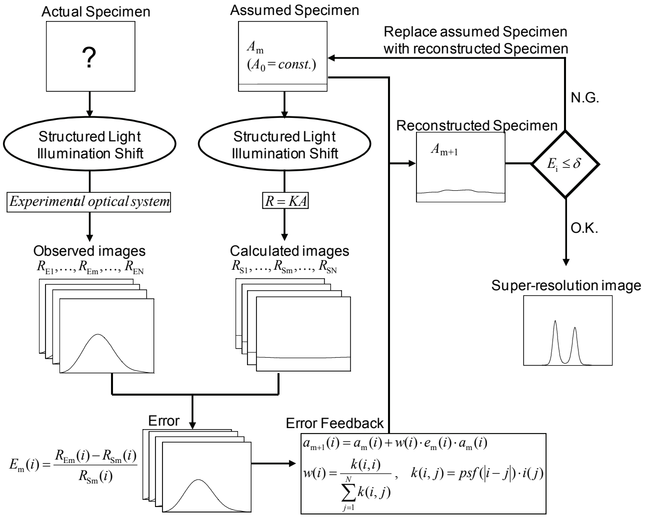

Fig. 2 Block diagram of iterative image reconstruction using multiple images with spatial shift of structured illumination

3.Sub-pixel Sampling Based on Structured Illumination Shift Method

3.1 Relationship between CCD Pixel Size and Resolving Power

The resolving power of an optical image is limited by diffraction determined by numerical aperture of an objective lens and wavelength of illumination. But in actual imaging, we can obtain the optical image as a digitalized image with a spatial sampling module such as CCD or CMOS. Digitalized images are equal to sampled and quantized images. In terms of digital images, resolving power refers to the size of pixels of CCD utilized in construction of the image.

The size of the pixels, which is the distance between each pixel, contained in a digital image is known as the sampling interval determined by a magnification of optics and spatial sampling device like CCD. The numerical value of each pixel in the digital image represents the intensity of the optical image averaged over the sampling interval. Features seen in the digital image that are smaller than the digital sampling interval will not be represented accurately in the digital image. The Nyquist criterion requires a sampling interval equal to twice the highest specimen spatial frequency to accurately preserve the resolving power of the resulting digital image. A majority of digital sampling module for an optical microscopy have a fixed maximum sampling interval, which cannot be adjusted to match the spatial frequency of a specimen. It is important to choose a digital sampling module and optical magnification that can meet the minimum resolving power requirements of specimen features, so that wider imaging area can be obtained. In situations where higher measurement speed (wider imaging area) is needed, then the optical resolving power is superior to the spatial density of CCD pixel. Therefore, the resolving power of the resulting digital image is limited by the spatial sampling. Diffraction-limited and digitalized images of 2-points specimen are shown in the Fig.3, where D_{Gap} is the gap between 2-points, D_{Pixel} is the CCD pixel size (sampling interval). And optical condition of imaging is shown in the table 1. In the Fig.3(b) and (c), the 2-points specimen is resolved as digital image with 2 intensity peaks because D_{Gap} is bigger than D_{Rayleigh}. In the Fig.3(d), the 2-points is not resolved because D_{Gap} is smaller than twice the D_{Pixel} as noted in the Nyquist criterion, although the 2-points are optically resolved.

In order to apply optical resolving power improvement by structured illumination to digital images without compromising measurement speed, we have proposed sub-pixel sampling with sub-pixel spatial shifts of the structured illumination described in the next section.

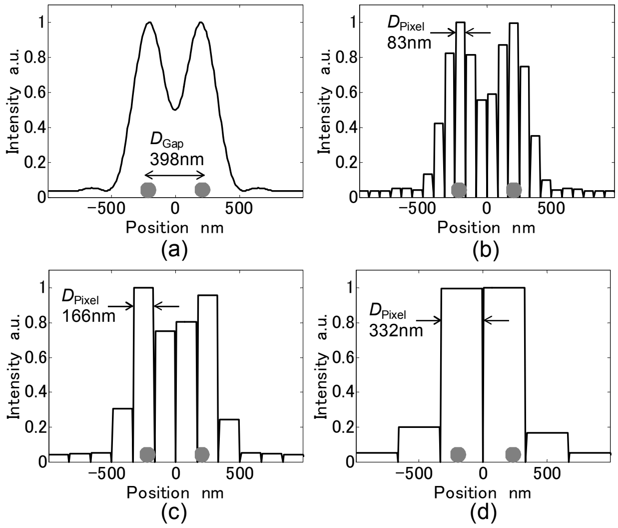

Fig. 3 Images of 398nm-gapped 2-points specimen with various pixel sizes and uniform illumination
(a) Out of consideration of pixel size, (b) Condition of D_{Pixel}=83nm
(c) Condition of D_{Pixel}=166nm, (d) Condition of D_{Pixel}=332nm

Table 1 Optical condition of imaging

Wavelength of illumination light	532nm
Numerical aperture of objective lens	0.95
Diffraction limit by Rayleigh criterion: D_{Rayleigh}	342nm

3.2 Numerical Simulation of Sub-pixel Sampling and Resolving Power Improvement

Numerical simulations for verification of resolving power improvement with multiple digital image reconstruction based on sub-pixel spatial shifts of the structured illumination were performed.

The results of diffraction-limited and digitalized images with 3 kinds of sub-pixel-shifted positions of the structured illumination are shown in the Fig.4. Fig.4(a) shows the distribution of structured illumination and 2-points specimen. If the structured illumination is spatially shifted, optical excitation from 2-points specimen was changed according to the intensity of structured illumination. So, the diffraction limited images shown in the Fig.4(b) and the digitalize images shown in the Fig.4(c) are modulated. As a result, sub-pixel spatial shift of the structured illumination is transferred to a digital image modulation shown in the Fig.4(c).

The Fig.5 shows the results of reconstruction of multiple digitalized images with sub-pixel spatial shifts of the structured illumination. The method of reconstruction is described at 2.2, and the optical condition of imaging and the condition of reconstruction is shown in the table 1 and the table 2 respectively. Diffraction limited and digitalized images with uniform illumination at different specimen and different size of CCD pixel are shown in the Fig.(a) and (c), where 2-points specimen are not resolved due to not only the diffraction limit but also the CCD pixel size bigger than the half of the gap of the specimen. The result of reconstruction with the specimen of (a) is shown in the Fig.(b), where the 398nm-gapped 2-points specimen was clearly resolved. It was found in this result that the information of sub-pixel spatial shifts of structured illumination was reflected in the reconstruction. The Fig.(d) shows the result of the reconstruction under the severe condition for resolving. The 132nm-gapped 2-points specimen with the CCD pixel size of 664nm was resolved, so it was suggested that the proposed method has the possibility to improve the resolving power not only beyond the diffraction limit but also beyond the limited determined by the CCD pixel size.

Table 2 Condition of reconstruction

Spatial pitch of structured illumination	500nm
Size of sub-pixel spatial shift of illumination	10nm
Number of images used in reconstruction	50
Pixel size for registration of reconstructed results	8.3nm
Iteration times of reconstruction	1000

3.3 Resolving Power Verification by MTF

The resolving power and performance of an optical imaging system can be characterized by a quantity known as the modulation transfer function (MTF), which is an ability to transfer contrast from the specimen to the intermediate image plane at a specific resolving power. The MTF is useful for characterizing not only traditional optical systems, but also digital imaging systems.

A sinusoidal chart specimen, representing 100 percent contrast (MTF intensity = 1) is presented on the left-hand side of the Fig.6. The resulting image produced by diffraction-limited imaging and digitalization is shown on the right side of the Fig.6, and appears as a discrete intensity distribution that has reduced contrast of 40 percent (MTF intensity = 0.4).

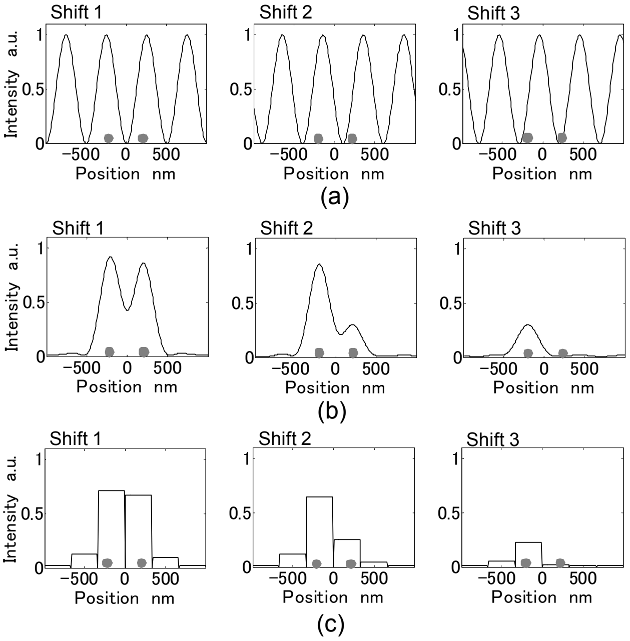

Fig. 4 Result of diffraction-limited and digitalized images with 3 kinds of sub-pixel-shifted positions of the structured illumination
(a) 398nm-gapped 2-points specimen with structured illumination
(b) Diffraction-limited image of 2-points specimen
(c) Digitalized image with D_{Pixel}=332nm

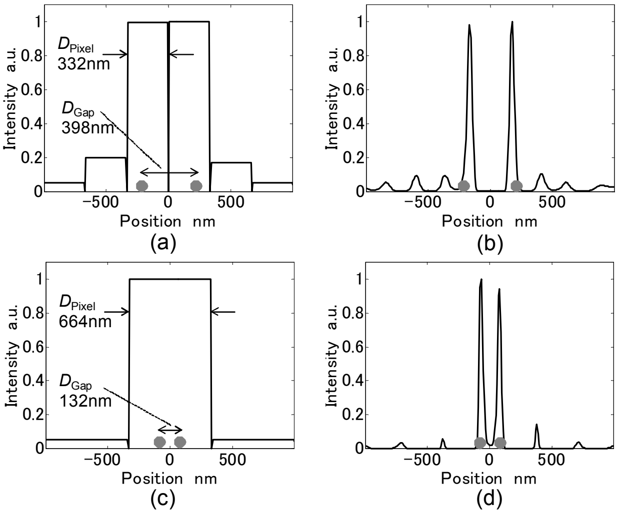

Fig. 5 Result of reconstruction of multiple digitalized images with sub-pixel spatial shifts of the structured illumination
(a) Diffraction limited and digitalized image with uniform illumination (D_{Gap}=398nm and D_{Pixel}=332nm)
(b) Reconstructed specimen of (a)
(c) Diffraction limited and digitalized image with uniform illumination (D_{Gap}=132nm and D_{Pixel}=664nm)
(d) Reconstructed specimen of (c)

The number of spatial period of sinusoidal chart per unit interval in a specimen is referred to as the spatial frequency. Therefore, MTF curve, which is the relationship between contrast and spatial period of specimen, is obtained by the Fourier analysis of resulting images of sinusoidal chart specimen with various period.

In order to verify resolving power improvement with sub-pixel sampling with sub-pixel spatial shifts of the structured illumination quantitatively, the MTF analyses using sinusoidal chart specimen were performed. The MTF curve plots of sinusoidal chart, diffraction-limited images, digitalized images and reconstructed specimen with multiple digital images are shown in Fig.7. The optical condition of imaging and the condition of reconstruction is shown in the table 1 and the table 2 respectively. If the CCD pixel size is much smaller than the size of the diffraction limit (D_{Pixel}=20nm shown in the Fig.7(a)), the MTF curve of digital images is almost the same of the curve of diffraction-limited images. And then, the improved resolving power by reconstructed specimens was about 5 cycle/μm at MTF intensity of 0.2, which means the limit of resolving based on the Rayleigh criterion. It was approximately twice as high as the resolving power of digitalized images, which was about 2.5 cycle/μm at MTF intensity of 0.2. If the CCD pixel size is almost the same as the diffraction limit (D_{Pixel}=313nm shown in the Fig.7(b)), the MTF intensity of digital images were decreased contrasted with diffraction-limited images. Although the MTF intensity of reconstructed specimen was reduced due to bigger CCD pixel size, the resolving power at MTF intensity of 0.2 was about twice as high as digitalized images, and was about 1.5 times as high as diffraction limited images. The Fig.7(c) shows the results in the situation, where CCD pixel size is much bigger than the diffraction limit (D_{Pixel}=625nm). The MTF curve of reconstructed specimen was distorted due to decreased sampling frequency (bigger CCD pixel size). However the resolving power of reconstructed specimens at MTF intensity of 0.2 was 3 cycle/μm, which is superior to diffraction-limited images.

4. Conclusions

In order to improve the resolving power without narrowing the visual field area of optical imaging system, we focused attention on sub-pixel sampling with structured illumination shift method. The relationship between CCD pixel size and resolving power was investigated base on the diffraction-limited imaging and digitalization. And then, numerical simulations for verification of resolving power improvement with multiple digital image reconstruction based on sub-pixel spatial shifts of the structured illumination were performed. As a result, the proposed method has the possibility to improve the resolving power not only beyond the diffraction limit but also beyond the limited determined by the CCD pixel size. Moreover, to verify resolving power improvement quantitatively, the MTF analyses using sinusoidal chart specimen were performed. By a series of the MTF analyses, the resolving power improvement by the proposed method was confirmed even with the bigger CCD pixel size than the diffraction limit.

ACKNOWLEDGEMENT

This work has been supported by the Ministry of Education, Culture, Sports, Science and Technology, Grant-in-Aid for Special Purposes, 20569001.

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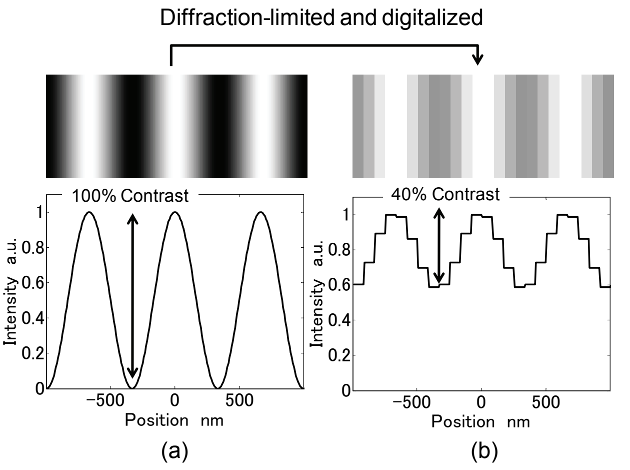

Fig. 6 Decreased contrast of sinusoidal chart specimen by diffraction-limited imaging and digitalization,
Spatial period of sinusoidal chart = 1.5 cycle/μm
(a) sinusoidal chart specimen (MTF intensity = 1)
(b) Diffraction-limited and digitalized image (MTF intensity = 0.4)

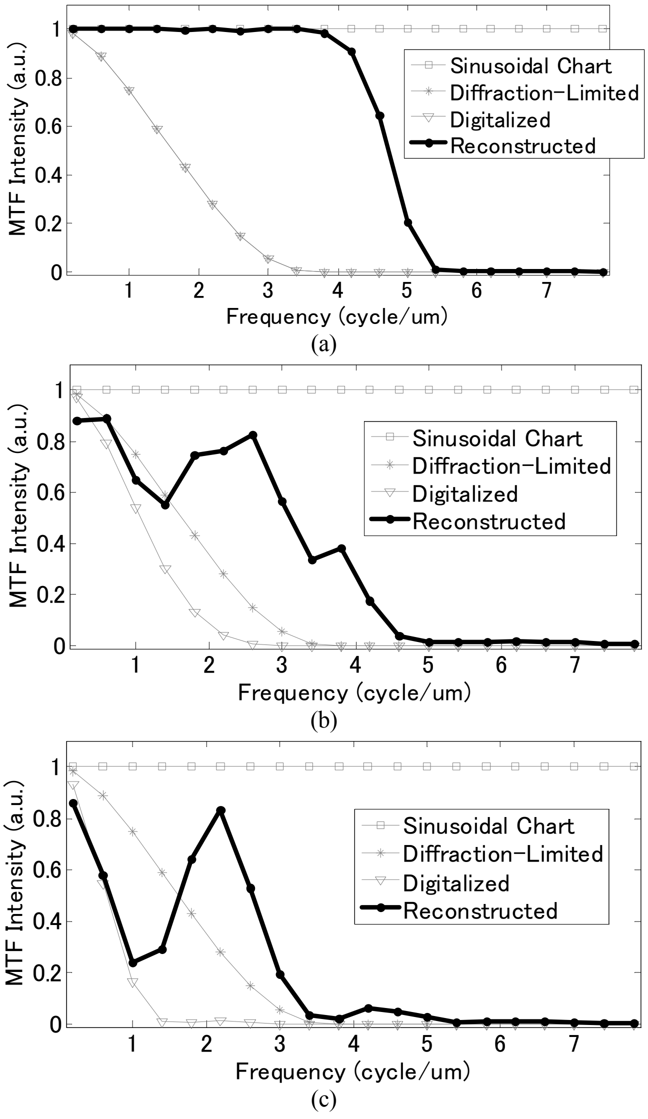

Fig. 7 MTF curve plots of sinusoidal chart, diffraction-limited images, digitalized images, and reconstructed specimen by multiple digital images with sub-pixel spatial shifts of structured illumination
(a) D_{Pixel}=20nm, (b) D_{Pixel}=313nm, (c) D_{Pixel}=625nm