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Review

Resolution Enhancement Techniques for Optical Lithography and Optical Imaging Theory

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Production of a fine pattern is necessary to get a high integration degree of integrated circuits. The conventional methods which utilize high numerical aperture and short wavelength exposure are limited by designing and manufacturing of a practical lens and make the focus depth narrow. Resolution enhancement techniques (RETs) have, therefore, been required and proposed. This paper introduces a phase-shifting mask, a typical RET, points out the problems and inconsistencies of conventional optical imaging theory and explains the image formation concept of expansion of plane waves. Essentially using this concept, an attempt is also made to describe some other typical RETs with potential.

Key words: lithography, imaging theory, optics, super resolution, resolution enhancement, imaging

1. Introduction

As the degree of integration of integrated circuits (IC) has recently become very high and the minimum pattern size very fine, these circuits have been made principally by reduction projection optical lithography. Figure 1 shows the transition of the minimum pattern size and the degree of integration of DRAM (dynamic random access memory). The minimum line width indicates the width of a line or space between lines of a pattern. Higher integration has been achieved by finer pattern and larger chip size. The minimum pattern size has been reduced by approximately a factor of four and the chip area increased by a factor of four in three generations. To date, the higher integration has been primarily achieved by higher numerical aperture and shorter wavelength exposure. The numerical aperture, however, is limited to 1 in principle except for oil immersion and may be limited to about 0.7 by the optimal design and manufacture of a practical lens. Shortening the wavelength of exposure light is restricted by light source and lens materials. Moreover, both higher numerical aperture and shorter wavelength make the focus depth narrower. For these reasons, high resolution cannot be obtained solely by improving the projection lens, and thus demand has risen for the development of resolution enhancement techniques (RETs).

To discuss RET, the typical configuration of a stepper, the reduction projection exposure apparatus is shown in Fig. 2. The light from a mercury high pressure lamp located in one focus of an ellipsoid mirror is focused on another focus. The light is then collimated to be parallel and is trimmed by a band path filter to have the bandwidth required by the chromatic aberration of the projection lens. To reduce the nonuniformity of illuminance on the wafer, a fly's eye lens is adopted. The source is reimaged at each exit surface of each fly's eye elements. Since optical parameters such as size of the source, magnification by ellipsoid mirror, focal length of collimator lens and aperture size of the fly's eye element have proper values, the entire image on the exit surface of the fly's eye lens can be regarded as an incoherent second surface source and the mask is illuminated by this incoherent source through the main condenser lens. The mask pattern is reimaged on the wafer through the projection lens.

The size of the second surface source, which is the size of the entire exit surface of the fly's eye lens, corresponds to the numerical aperture of illumination. By changing this size, the degree of spatial coherence on the mask can be controlled to have optimum imaging performance. In the case of conventional circle illumination, the coherence factor of σ is defined by $\sigma=\mathrm{NA_S}/\mathrm{NA_0}$. Here, NAs is the numerical aperture of illumination and $\mathrm{NA_0}$ is that of the projection lens in the object (mask) space. Also, the magnification β of the projection lens is represented by $\beta=\mathrm{NA_0}/\mathrm{NA_I}$ where $\mathrm{NA_I}$ is the numerical aperture of the projection lens in the image (wafer) space.

Referring to Fig. 2, we can consider not only the conventional RETs such as large numerical aperture and short wavelength of exposure light, but also another methods like controlling the shape of the second source,[1,2] modifying the mask,[3,4] controlling the pupil function of the projection lens[5,6] and multiple exposure with moving the wafer or mask.[7-9] Some typical RETs are classified by both position and physical method in Table 1. Applying the property of polarization light is also considered.[10] In contrast to the conventional idea, a method which controls the spatial coherency on the source is also proposed,[6] and combinations of the methods shown in Table 1 are also considered, among them: controlling both the shape of source and pupil function,[11,12] and the combination of annular illumination and half tone phase-shifting mask.[13] Developing an illumination system, which produces a spatial incoherent surface source from a coherent source, is also an important subject.[14]

RETs can be classified to three groups by their aims as shown in Table 2. Phase-shifting mask,[3,4] annular illumination and an illumination controlled method called SHRINC[1,2] (Super High Resolution by IllumiNation Control) are techniques for getting high contrast image in the region of conventional resolution limit. A multiple

Table 1. Classification of RETs from view point of its position of stepper and physical methods.

	Source	Mask	Pupil	Wafer
Exposure wavelength	Excimer laser[14]			
Shape control	Annular illumination SHRINC[1,2]		Apodization	
Coherent	MIRACO[6]			
Phase control		Phase-shifting mask[3,4]	Super-FLEX[5]	
Incoherent			SFINCS[6]	
Polarization	Polarized illumination	Polarized mask[10]	Polarized pupil	
Multi-exposure				FLEX[7], NOLMEX[8,9]

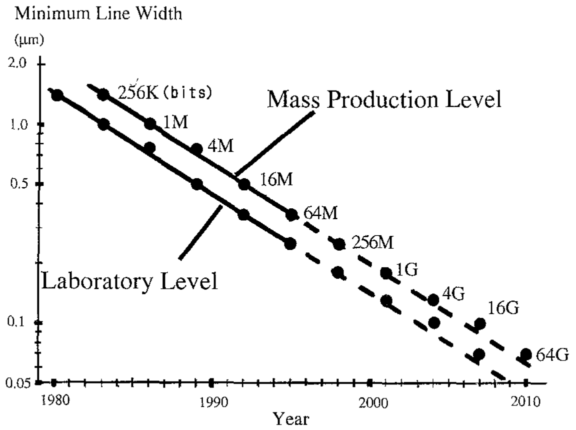

Fig. 1. The transition of the integration degree of DRAM.

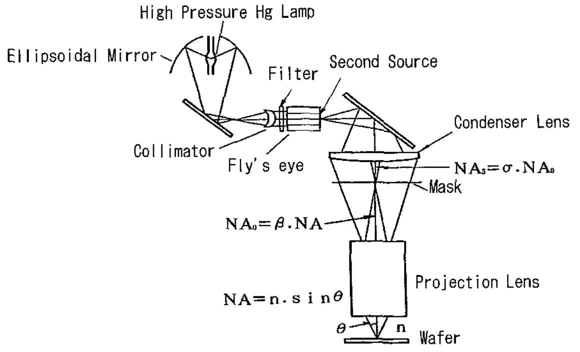

Fig. 2. Schematic configuration of typical stepper.

exposure method with moving focus position (FLEX[7]; focus latitude enhancement exposure) and multiple foci exposure method (Super-FLEX,[5] SFINCS[6]:Spatial Filter for INCoherent Stream) are those for getting large focus depth. Large focus depth is required in projection optical lithography because of wafer flatness error, resist thickness, uneven surface of a device and focus adjustment error. The multiple exposure method with moving wafer parallel to the image plane and using non-linear sensitive resist (NOLMEX[8,9]:Non-linear Multiple EXposure) obtains higher resolution than do conventional methods. From the viewpoint of conventional optical imaging theory, the phase-shifting method may be thought to get a finer pattern than the conventional optical limit, and it is also classified in this group.

Table 2. Classification of RETs from a view point of its aimes.

Resolution enhancement techniques (Classified by their aims)	
Image contrast is higher than that of conventional method	Phase-shifting method, SHRINC
Large focus depth	FLEX, SFINCS
Image period is finner than diffraction limited period	NOLMEX, (Phase-shifting method)

Table 3. Classification of RETs from a view point of fidelity.

Resolution enhancement techniques (Classified by fidelity between wafer pattern and mask pattern)	
Wafer pattern is fabricated with fidelity of mask pattern	SHRINC
Wafer pattern is fabricated without fidelity of mask pattern	Phase-shifting method, NOLMEX

RETs can also be classified in two groups by their fidelity between mask pattern and resist pattern as shown in Table 3. Projection optical lithography is different from conventional optical microscopy and does not require fidelity. In the phase-shifting mask method, the degree of fidelity is rather low in that the sign of amplitude is neglected; in the NOLMEX-method, the final image pattern is not at all coincident with the patterns generated by each exposure. Since deterioration of the fidelity becomes more critical as pattern size becomes finer, the compensation mask for the diffraction proximity effect has been discussed.[15]

In this paper, the RETs in optical projection lithography are explained. The image formation concept of the expansion of plane waves (plane wave decomposition) is described, so that the principal of the phase-shifting method is understood. Since clearly establishing the imaging theory is very valuable to improving and further developing RET, problems and inconsistencies of the conventional theory are pointed out. Moreover, an attempt is made to describe some of the typical RETs with potential using the concept of expansion of plane waves.

2. Phase-Shifting Method and Optical Imaging Theory

The phase-shifting method was invented by Dr. M. D. Levenson and the present author independently.[3,4] This method is explained along with the process of the author's invention and some misunderstandings of conventional optical imaging theory are discussed.

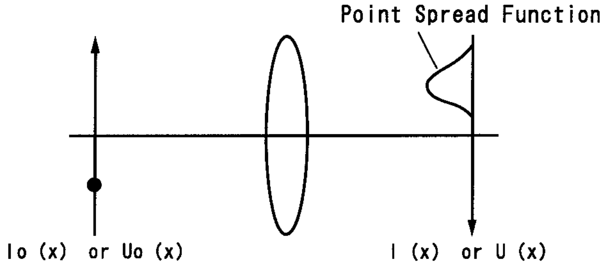

Fig. 3. Imaging by the projection lens.

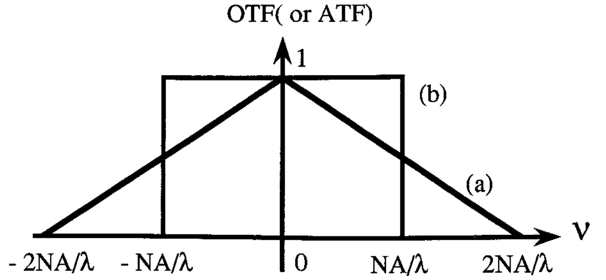

Fig. 4. Characteristic of OTF. (a) OTF of incoherent object (intensity), (b) ATF of coherent object (amplitude).

2.1 Phase-Shifting Method

The image performance of incoherent image formation can be evaluated by OTF (optical transfer function). As shown in Fig. 3, if the point spread function $i(x)$ is isoplanatic (in other words, is shift-invariant) in the image plane, the distribution of image intensity $I(x)$ can be represented by Eq. (1);

$$I(x)=I_0(x)\otimes i(x)\,, \tag{1}$$

where $\otimes$ means convolution. Because we discuss the fundamental characteristic of optical image formation, we use the 1-dimensional representation and the magnification is regarded as equal to 1 for convenience in this paper. Using the convolution theorem of Fourier transform,

$$\tilde{I}(\nu)=\tilde{I}_0(\nu)\cdot\tilde{i}(\nu) \tag{2}$$

is given. Here, ν is the spatial frequency and ~ means Fourier transformed function. This equation means that the Fourier transform of intensity distribution of object $\tilde{I}_0(\nu)$ is transformed to that of image $\tilde{I}(\nu)$ and the Fourier transform of the intensity point spread function $\tilde{i}(\nu)$ acts as a linear filter. In other words, the OTF is introduced as the Fourier transform of intensity point spread function in the case of an incoherent object. In the case of a coherent object, the same relations can be derived using amplitude functions as the following equations:

$$U(x)=U_0(x)\otimes u(x) \tag{3}$$

$$\tilde{U}(\nu)=\tilde{U}_0(\nu)\cdot\tilde{u}(\nu)\,. \tag{4}$$

Here, $U_0(x)$, $U(x)$ and $u(x)$ are amplitude functions of object, image and point image, respectively. $\tilde{U}_0(\nu)$, $\tilde{U}(\nu)$ and $\tilde{u}(\nu)$ are those Fourier transform functions. The OTF is introduced as the Fourier transform of amplitude point spread function in the case of a coherent object. Strictly speaking, we must call it ATF (amplitude transfer function) in this coherent case.

In conventional discussion, the characteristic of OTF is as shown in Fig. 4. Here, the cut-off frequency is given as 2NA/λ in an incoherent object and NA/λ in a coherent object; in the latter, only the amplitude is discussed, not intensity. However, since we can observe or detect the intensity, but not the amplitude, we must also discuss the intensity distribution on the image in the case of a coherent object. As the cut-off frequency of amplitude distribution is NA/λ, we can assume that the pattern with the frequency 2NA/λ can be obtained. To confirm this idea, I consider the image formation by using the expansion of plane waves.

As shown in Fig. 5(a), we can intuitively understand the image formation as follows. The object is illuminated by the plane wave from the source, this plane wave is diffracted by the object, it transmits through the lens and at last the image intensity distribution is performed by

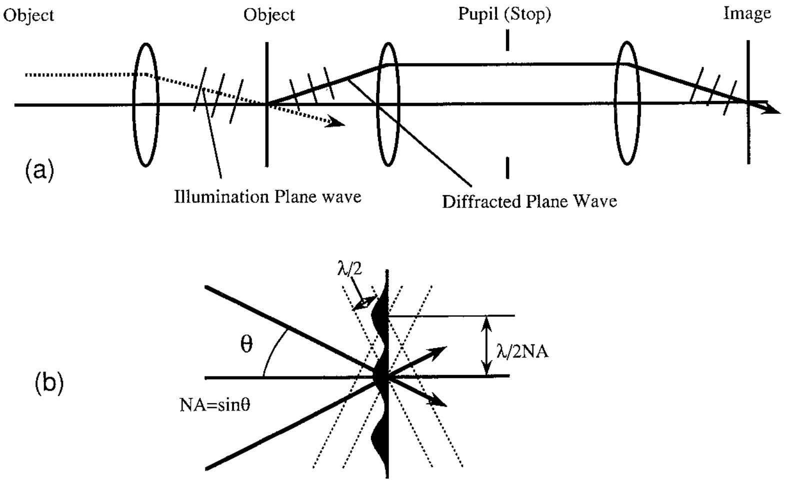

Fig. 5. Imaging by the projection lens.

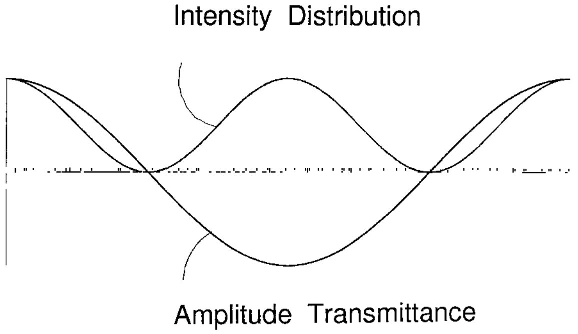

Fig. 6. Amplitude transmission of object.

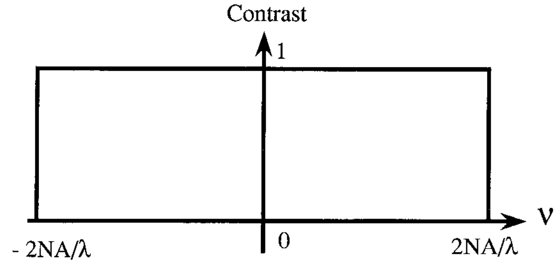

Fig. 7. Characteristic of optical transfer function.

interferences between the plane waves. We can easily tell from this figure that the fine pattern of frequency 2NA/λ is caused in spite of the illumination condition as shown in Fig. 5(b). Considering the case under coherent illumination, we find that if the phase-object has the amplitude transmittance shown in Fig. 6, two symmetrical diffracted plane waves are caused by the object. The amplitude of this object is represented by the equation:

$$U(x)=\cos(2\pi\nu_0 x)=\frac{1}{2}[\exp(i2\pi\nu_0 x)+\exp(-i2\pi\nu_0 x)]\ , \quad (5)$$

where, ν_0 is the spatial frequency of amplitude. These exponential terms correspond to the 1st and the −1st order diffracted waves, respectively. Under coherent illumination (illumination by plane wave propagating parallel to the optical axis), if the diffracted waves can go through the lens, they perform the pattern of frequency of $2\nu_0$ by interference. The intensity distribution of image is given by

$$I(x)=\cos^2(2\pi\nu_0 x)=\frac{1}{2}[1+\cos(4\pi\nu_0 x)]\ . \quad (6)$$

Therefore, as shown in Fig. 7, contrast of the image is maintained at 1 below the frequency of 2NA/λ.* On the other hand, as shown in Fig. 4, since the OTF, which corresponds to contrast, of an incoherent object becomes zero at the cutoff frequency of 2NA/λ, it cannot get actual resolution of optical lithography near the cutoff frequency.

The mask pattern shown in Fig. 6 is not practical for lithography, while the black and white pattern is realistic. A more practical mask having the phase-shifter as shown in Fig. 8 was developed by the author.[3,4]

Referring to Fig. 8(a), the effect of the phase-shifting mask is explained as follows. Under the coherent plane wave illumination, the 0th, the 1st and the −1st diffracted waves are caused by the conventional line and space pattern mask. On the contrary, when the phase-shifting mask is used, the 0th order diffracted wave vanishes as a result of the destructive interference between the light from an ordinary aperture and that of the phase-shifter aperture. Since the period of the phase-shifting mask is made twice that of the conventional mask by alternating phase-shifters, the diffracted direction cosine of the 1st and the −1st diffracted plane waves is reduced to half and they can go through the lens even in the high frequency original pattern.

The depth of focus becomes larger with the phase-shifting mask because the pattern is fundamentally fabricated by two beam interference. Also, the phase-shifting mask is believed to utilize the non-linearity between amplitude and intensity.

2.2 Improvements of Phase-Shifting Method

In the real IC pattern, some patterns are not one dimensional and not periodic. The demand for high density integration for logic IC has called for an isolated fine pattern. The principle of the phase-shifting mask can also be understood from another viewpoint. As shown in Fig.

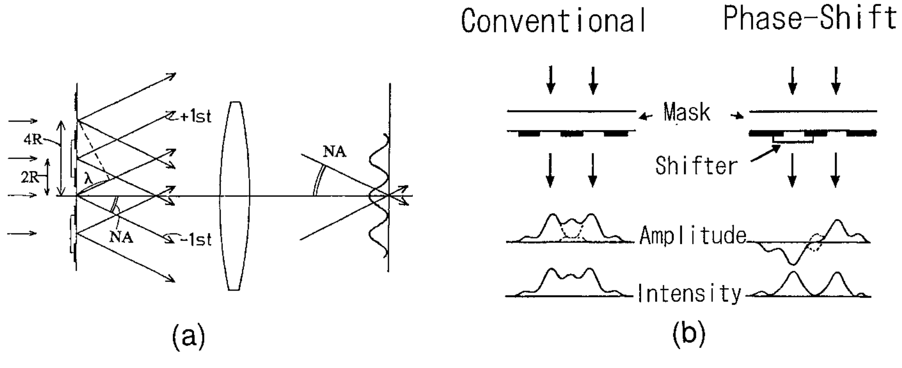

Fig. 8. Schematic figure of Shibuya-Levenson type phase-shifting mask.

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*This issue is briefly discussed in the book titled "Introduction to Fourier-Optics" by Goodman.[16] However, the concrete model is not discussed in depth nor is the practical phase-shifting mask mentioned.

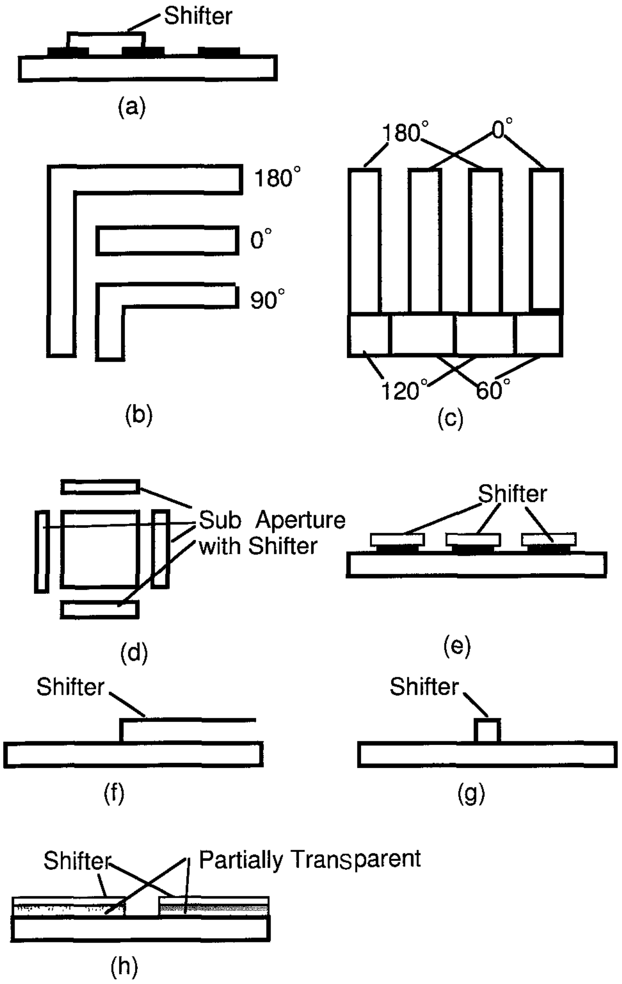

Fig. 9. Some improvements of phase-shifting mask.

8(b), the intensity at the midpoint between two apertures disappears with the destructive interference between light from a normal aperture and that from a neighboring phase-shifter aperture. This is especially applicable considering an isolated pattern.

Figure 9 shows types of phase-shifting masks[17]: (a) is the principle phase-shifting mask called Levenson or Shibuya-Levenson (Levenson-Shibuya) type[17,18]; (b) is for a 2-dimensional pattern and the phase shift is 90 and 180 deg[3,18]; (c) is also for a 2-dimensional pattern and controls the interference effect at the boundary of two phase shifters[19]; and (d) to (h) are basically useful for isolated pattern, thus their performance cannot be adequately discussed from viewpoints of spatial frequency and expansion of plane waves; (d) has sub apertures with phase-shifter.[20] The destructive interference between the wave from an original aperture and the wave from a sub aperture with a phase-shifter makes pattern fine; (e) is a so-called edge enhanced type[21] and is fundamentally similar to (d); (f) uses the destructive interference at the edge of the shifter[22-24]; (g) uses the destructive interference between the wave from the isolated shifter and a background wave[25]; and (h) is a so-called half-tone phase-shifting mask.[26] The destructive interference between the wave from an original aperture and the weak background wave makes a fine pattern. Here, the light transmits a little through the dark part of mask and the phase is shifted. As mentioned above, the phase-shifting mask is very useful for any patterns.

Optimization of the arrangement of phase-shifters in a complicated mask pattern was also investigated.[27]

2.3 *Optical Imaging Theory*

As explained in Sect. 2.1, the concept of image formation considering plane waves and their interferences is very valuable and useful for developing and investigating the RET. In conventional optical imaging theory described in many books, however, this concept has not been clearly explained, nor has the mathematical propriety been revealed. Some problems or inconsistencies of the conventional optical imaging theory are now pointed out, because it will not only be helpful for development of a novel RET but also educationally instructive.

The conventional optical imaging theory based on point image is clear mathematically as shown in Eqs. (1)–(4); what transmits through the lens is represented by the equation:

$$\tilde{U}(\nu)=\int U(x)\cdot\exp[-i\cdot 2\pi\cdot\nu\cdot x]dx \qquad (7)$$

where, ν is the spatial frequency and λ is the wavelength of exposure light. Considering the physical meaning of the exponential term, we notice that this form is similar to the plane wave and, in fact, reveals the amplitude of plane wave on the object (image) plane. By introducing the direction cosine ξ of normal vector of plane wave, another representation is given by

$$\tilde{U}(\xi)=\int U(x)\cdot\exp[-i\cdot(2\pi/\lambda)\cdot\xi\cdot x]dx\,. \qquad (8)$$

This equation further confirms that the exponential term corresponds to the plane wave. The image formation can be determined by the expansion of plane waves.

This fact has not yet been clearly stated, however. In many textbooks, the image formation is fundamentally explained as being based on the point spread function, and Fourier optics is instantly introduced by the Fourier transform of this function. Moreover, discussion and exact proof of equivalency between isplanatism and propriety of expansion of plane waves have also not been mentioned. This may be mentioned only in the footnotes of "Principles of Optics" by Born and Wolf.[28] The necessary and sufficient condition of propriety for the expansion of plane waves is that the Fresnel number must be sufficiently larger than 1,[29] and the isoplanatic condition is that both the large Fresnel number and the sine condition are satisfied.[29] Nevertheless, the Fresnel number is not described in many of the textbooks of optics. In addition, the tracing formulae of Gaussian beam is necessary only when the Fresnel number is small. It is therefore desirable that the necessary and sufficient condition for fulfilling Fourier optics and the Fresnel number are introduced in an elementary level textbook of optics.

In most cases, it is explained that the intensity distribu-

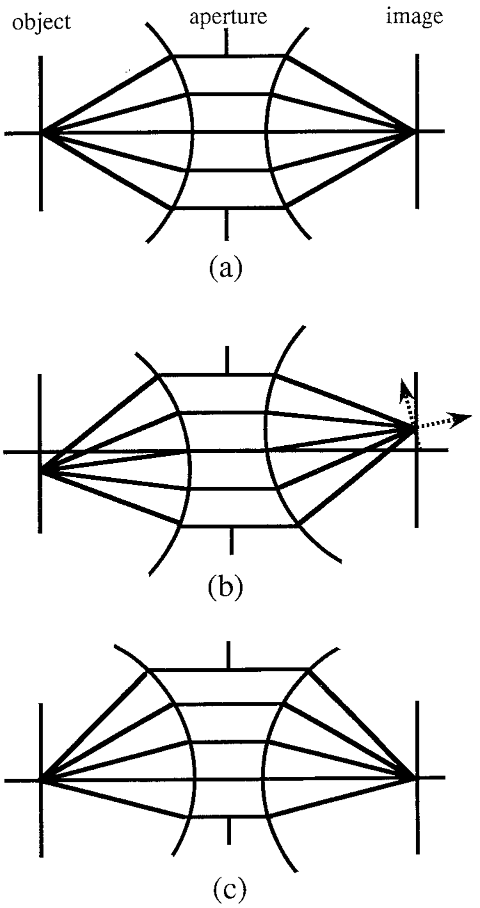

Fig. 10. Equivalency between off-axis imaging and on-axis imaging with pupil shifting.

tion of a defocused image must be calculated by using Fresnel diffraction which is regarded as a more accurate approximation than Fraunhofer diffraction. However, in the theory based on the expansion of plane waves, it is meaningless to distinguish Fresnel diffraction from Fraunhofer diffraction at least in the isoplanatic image formation.

Also, even though H. H. Hopkins pointed out and emphasized the meaning of pupil coordinate by introducing the concept of canonical coordinates,[30] this is not adequately understood by many engineers and designers. This coordinate fundamentally corresponds to the direction cosine ξ in Eq. (8). A typical example of misunderstanding would be that, in calculating the point spread function of an off-axis point image, the local coordinate shown by dotted lines in Fig. 10(b), which has no clear physical meaning is used.[28] As shown in Fig. 10, the case of an off-axis point image (b) is similar to that of an on-axis point image with shifted aperture (c). We can thus discuss an off-axis point in the same manner as an on-axis object point.

The insufficient understanding of the meaning of pupil coordinates reflects the wrong derivation of the sine condition in the presence of spherical aberration. Even Hopkins misunderstood.[31] In order to derive the correct condition,[32,33] we must adequately understand the meaning of pupil coordinates. This condition is also useful for designing a projection lens for optical lithography, particularly, for the one-sided terecentric lens. The one-sided terecentric lens means that the chief ray is parallel to the optical axis only in the image (wafer) space; this style was frequently used in the early days of stepper.

Despite the fact that the concept of expansion of plane waves has not been adequately mentioned in fundamental textbooks, it has been widely used by actual engineers and designers for optical discs, scanning microscopes and other instruments. It has also been used in the field of optical lithography, and some researchers have considered the optical system and represented equations by directly applying expansion of plane waves. However, even in such cases, misunderstandings exist. Hopkins stated that "In the case of image formation with coherent light, the object produces its Fourier spectrum on the entrance pupil reference sphere....".[30] This, however, is not proper. The relation of Fourier transform is fulfilled between the object and the plane of Fourier transform, which fundamentally exists at the stop, and the Fourier transform coordinate is proportional to direction cosine ξ ($=\sin\theta$). At least in view of the amplitude distribution of the spectrum on the pupil sphere and curvature and astigmatism of the entrance pupil, this is not correct. When we calculate the image distribution, if we postulate that the amplitude distribution of Fourier spectrum is produced on the reference sphere, we must consider the amplitude transformation factor from the entrance pupil to the exit pupil. This factor is introduced by Yeng and given by the Eq. (9)[34]:

$$\frac{\sqrt{\cos\theta'}}{\sqrt{\cos\theta}} \qquad (9)$$

where, θ is the angle between the entrance ray (normal vector of plane wave) and optical axis in the object space and θ' is that in the image space. However, the factor is not necessary in the scalar wave imaging theory at all because the relation of Fourier transform is fulfilled between the object and the stop. Strictly speaking, Yeng dealt with image formation by using scalar wave diffraction on the object (mask), considering the interference between vector plane waves on the image (wafer) and adopting θ' as the diffraction integral variable. Therefore, the factor given by the next equation must be multiplied in his theory:

$$\sqrt{\cos\theta'} \qquad (10)$$

In many practical cases, since NA ($=\sin\theta$) in the object space is small, the difference between Eq. (9) and Eq. (10) is negligible. But NA becomes large in future optical lithography, it will cause finite error. Of course, if NA becomes large, we must also use vector diffraction on the mask. In any event, it is very important that we correctly understand the concept of expansion of plane waves and the scalar wave imaging theory.[35,36]

The Fourier scalar imaging theory is an approximate theory which has an exact physical meaning, but it is a consistent theory. If we thoroughly understand it and adopt the direction cosine ξ as the pupil coordinate, the wrong factor of Eq. (9) is not introduced. This theory also adopts $\sqrt{\cos\theta}$ as the inclination factor of diffraction on the object.[35,36] In the case of an incoherent object, the surface is assumed to be Lambertian.[35] Then, considering the thermal equilibrium state, it can be confirmed that the principle of detailed balancing[37] between energy flow from object to image and that from image to object is consistent with this theory. It is also ascertained that OTF from object to image is equal to that from image to object.[35] On the contrary, in the above wrong treatment, these consistent relations are not satisfied.

The same fault has recently been revealed in a certain paper.[38] In spite of the fact that the expansion of plane waves has been taken into consideration and the importance of direction cosine as the pupil coordinate was emphasized, the wrong factor Eq. (9) was introduced in the scalar imaging theory. It was quite mysterious.

The problems of the conventional imaging theory have been pointed out in this section and the propriety of the expansion of plane waves mentioned. This expansion concept has been widely and practically used, however, it has not been widely understood in exact sense. It is hoped that its mathematical foundation and physical meaning will be exactly mentioned in public and broadly and correctly understood. This concept is also useful for use in a non-isoplanatic image formation.[39]

As shown in Fig. 8 (a) and (b), both the concept of the image formation based on point spread function and that on plane wave complement each other and will be applicable in the development of RET. These two aspects are assumed to be based on real space and Fourier space, respectively.

3. Another Resolution Enhancement Technology

Despite its not yet being thoroughly understood, the concept of the expansion of plane waves has actually been used in the field of optical lithography. In this section, a few typical or hoped-for RETs are discussed based on this expansion.

3.1 *Illumination Control Method*

The repetitive structural pattern of IC can be fabricated primarily by interference between the 0th and the ±1st order diffracted plane waves. Especially for fine pattern, as shown in Fig. 11(a), only the 0th and the ±1st order diffracted plane waves go through the projection lens. Since the ±1st diffracted waves of the illumination light from the center part of a source cannot go through, this part of the illumination does not contribute to image formation and thus reduces the contrast. Therefore, as shown in Fig. 11(b), by blocking the center part of the source and using annular illumination, we were able to obtain a high contrast fine pattern as required in optical lithography.

Moreover, carefully taking Fig. 11(b) into consideration, the ±1st diffracted waves of the illumination light from part-a of annular source does not go through the lens and reduces the contrast. The two perpendicular directions of periodical patterns offer a practical solution that the illumination source is composed of 4 small sources as shown in Fig. 11(c). This is the illumination control method called SHRINC.[1]

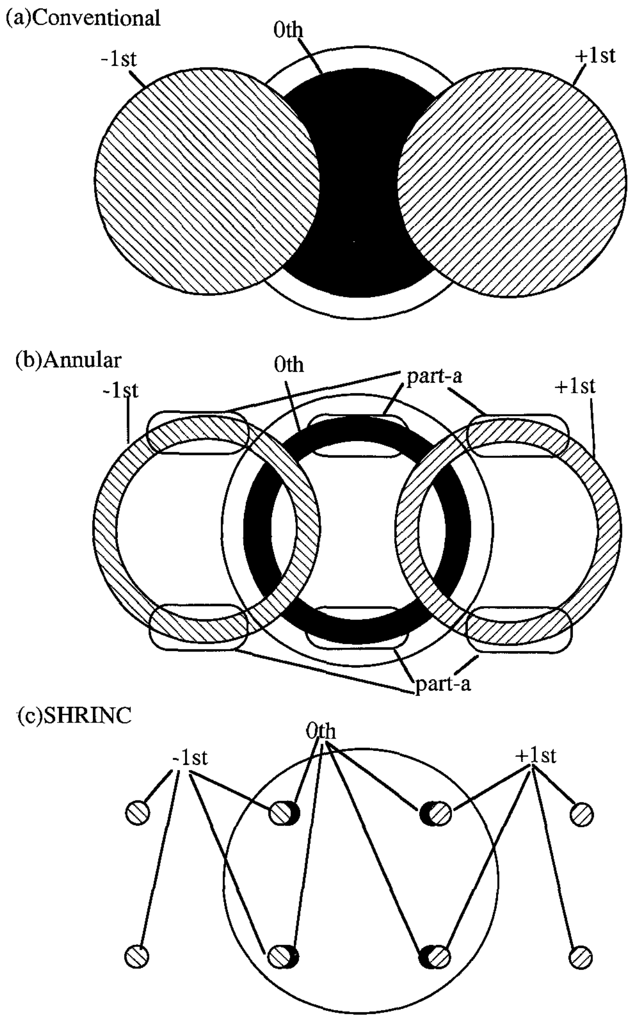

Fig. 11. Principle of illumination control methods.

3.2 *RET by Multiple Exposure Method*

A few multiple exposure methods have been proposed such as FLEX[7] and NOLMEX method.[8,9] FLEX is a method which multiplies exposures with moving focus position and is very useful in getting large focus depth for an isolated pattern. The NOLMEX method is used to multiply exposures with moving wafer perpendicular to the optical axis and using a non-linear sensitive resist. This may be the first method to actually get a finer pattern beyond the cutoff frequency of the projection lens. In this sense, the NOLMEX method may be strongly related to the concept of expansion of plane waves; thus the method is introduced here.

As stated before and shown in Fig. 5(b), the minimum repetitive structure of a pattern by optical imaging is caused by interference between the plane wave from the upper side of the pupil and that from the lower side. If the wafer is exposed only once, the finer pattern beyond the cutoff frequency of $2NA/\lambda$ cannot be fabricated at all. The

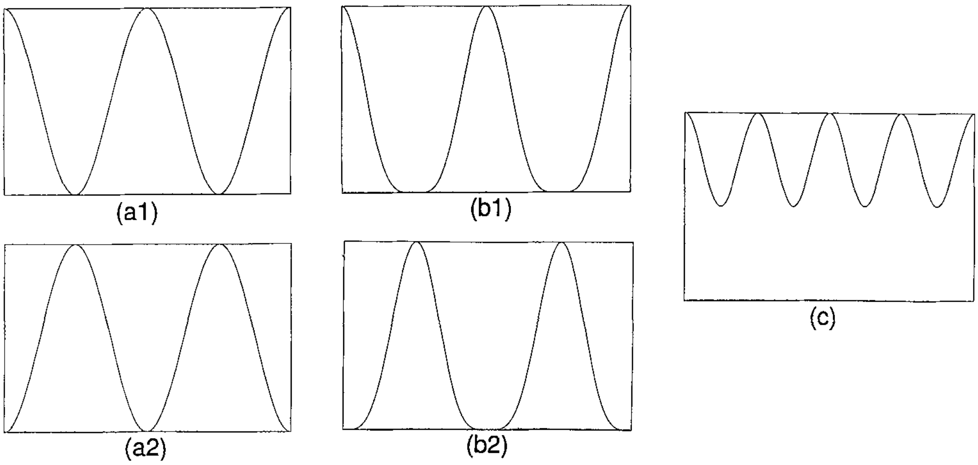

Fig. 12. Principle of NOLMEX.

NOLMEX method has been proposed to overcome this limitation.

The basic principle of the method is as follows. If two-photon absorption resist[40] is assumed to be utilized, the effective intensity distribution is the square of the actual exposure intensity. In Fig. 12, (a1) is the actual intensity distribution of the 1st exposure and (a2) is that of the 2nd exposure with a half-period lateral image shift. (b1) and (b2) are the effective intensity distributions of (a1) and (a2), respectively, and (c) is the sum of these two effective intensities. Using a phase-shifting mask with sufficiently coherent illumination, the contrast of the exposure intensity near the cutoff frequency of the projection lens can be enhanced to almost 1. Next, we double-expose a wafer, with the second exposure being performed after a half-period lateral movement of the wafer. The light intensity distribution for the first and the second exposures $I_1(x)$ and $I_2(x)$ and the effective light intensity distribution I_{eff} are represented as follows:

$$I_1(x)=1+\cos(2\pi\nu x)\,, \tag{11}$$

$$I_2(x)=1-\cos(2\pi\nu x)\,, \tag{12}$$

$$I_{\mathrm{eff}}(x)=I_1^2(x)+I_2^2(x)=3+\cos(4\pi\nu x)\,. \tag{13}$$

Here, ν is the spatial frequency of the actual intensity distribution of a single exposure. From these equations, when ν is near the cutoff frequency of projection lens $2\mathrm{NA}/\lambda$, the frequency of effective intensity of Eq. (13) is near $4\mathrm{NA}/\lambda$ and the contrast is 1/3. Namely, twice higher resolution is obtained.

It must be noted that if a linear sensitive resist is used, the sum of the two effective intensities I_1+I_2 of double exposure is constant all over the wafer and no pattern is fabricated.

It can thus summarized that the phase-shifting method utilizes the non-linearity between amplitude and intensity and the NOLMEX method utilizes that between actual intensity and effective intensity.

3.3 RET by Modification of Pupil Function

Several methods of controlling the pupil function of projection lens have been proposed. Here, two typical methods are described based on point spread function, but the defocus wave aberration is considered using the concept of expansion of plane waves. The aim with both is to get large focus depth.

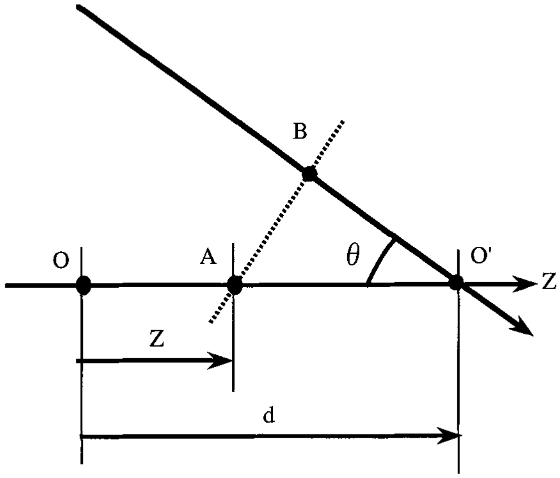

Fig. 13. Defocused wave aberration.

3.3.1 Phase controlled pupil filter

To get large focus depth, the pupil filter is used in the projection lens in a method called Super-FLEX.[5] The pupil function of this filter is the sum of two pupil functions which correspond to two different foci. Using focus direction Z and defocus position +d (point O′) and referring to Fig. 13, we can get the plane wave aberration of defocused point image (point A′) as Eq. (14):

$$W(\xi)=\overline{BO'}-\overline{AO'}=\frac{2\pi}{\lambda}(z-d)\cdot(1-\sqrt{1-\xi^2}) \tag{14}$$

Here, ξ is the pupil coordinate and is equal to the direction cosine of the normal vector of plane wave ($\xi=\sin\,\theta$). Introducing the original phase of defocused position (point O′) as $+\phi/2$ and approximating Eq. (14),

$$W(\xi)=\frac{\pi}{\lambda}(z-d)\cdot\xi^2+\frac{\phi}{2} \tag{15}$$

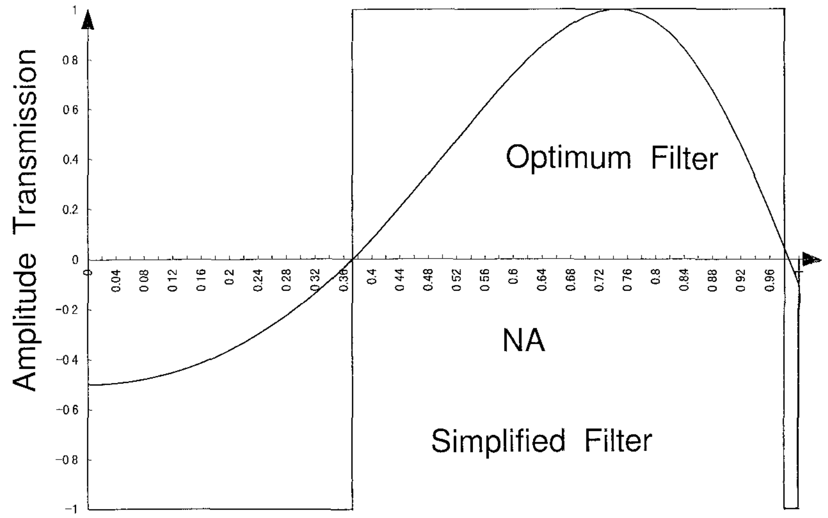

Fig. 14. Pupil function of coherent double exposure method.

is given.* Normalizing parameters by introducing the following equations,

$$\xi = r \cdot \mathrm{NA}, \quad z' = \frac{z}{\dfrac{\lambda}{2 \cdot \mathrm{NA}^2}}, \quad d' = \frac{d}{\dfrac{\lambda}{2 \cdot \mathrm{NA}^2}} \tag{16}$$

Eq. (17) is given:

$$W(r) = \frac{\pi}{2}(z' - d') \cdot r^2 + \frac{\phi}{2}. \tag{17}$$

Considering two symmetrically defocused positions and adding two wave aberrations, total wave aberration is given by

$$\begin{aligned}&\exp\left[i\left\{\frac{\pi}{2}(z'-d')\cdot r^2 + \frac{\phi}{2}\right\}\right] + \exp\left[i\left\{\frac{\pi}{2}(z'+d')\cdot r^2 - \frac{\phi}{2}\right\}\right] \\ &= \exp\left[i\frac{\pi}{2}\cdot z' \cdot r^2\right]\cdot\cos\left(\frac{\pi}{2}d'\cdot r^2 - \frac{\phi}{2}\right).\end{aligned} \tag{18}$$

In this equation, the exponential term means a conventional defocus aberration and cosine term means the pupil function introduced by two defocused image. Since this pupil filter cannot be actually manufactured, the approximation shown in Fig. 14 is adopted.

3.3.2 Pupil filter consisting of several incoherent parts

Another type of pupil filter with which to get large focus depth is inserted in the projection lens; this method is called SFINCS.[6] The pupil is divided into several annular regions. As shown in Fig. 15, the optical path difference between rays through different regions is larger than the coherence length of exposure light. Therefore, the light from one region is not coherent with that from another region.

The defocused wave aberration is approximately the function of square of pupil coordinate ξ. However in this method the real defocused wave aberration is limited in each region; the real defocused aberrations are W1, W2, W3 as shown in Fig. 15, and they are smaller than the original defocused aberration W_d. Therefore, we can get large focus depth. In other words, this method uses the incoherent sum of different so-called Bessel beams.

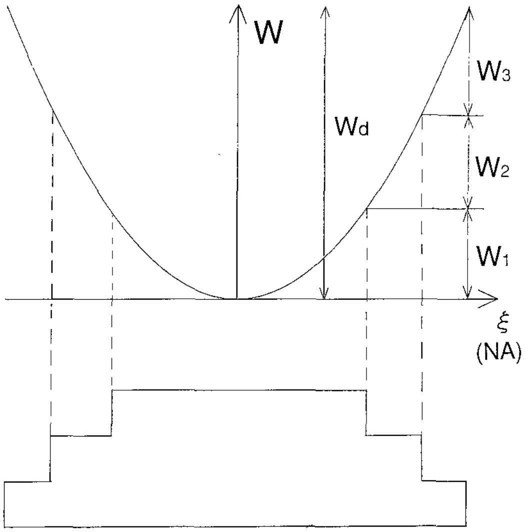

Fig. 15. Pupil function of SFINCS.

Most of the methods to control the pupil have been proposed by device manufacturers. Because of the severe requirement for accuracy in manufacturing the projection lens, manufacturing apparatus makers tend to avoid taking these methods into consideration. However, in the development of future RET, it is important not to be restricted by present manufacturing methods which pose some difficulties.

4. Summary

RET of optical lithography cannot be developed unless the optical imaging theory is thoroughly understood. Along with an explanation of the phase-shifting method

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*This approximation is not as appropriate if the numerical aperture is larger than around 0.6.[36] Furthermore, defocus aberration represented by Zernike polynomial is convenient but does not give the correct defocused wave aberration. These facts are not clearly written and not emphasized in fundamental textbooks on optical design.

and description of its invention process, the importance of the concept of expansion of plane waves was emphasized here and the problems of conventional optical imaging theory pointed out. Consideration based not only on the point spread function but also on the expansion of plane waves will be helpful in developing novel methods and improving those now in use. Several typical and hoped-for RETs described here can be understood using the concept of expansion of plane waves. It is hoped that the proposal made here will be valuable for development of RET and will also be instructive.

In future development, we must not forget that the large focus depth is required and fidelity is not necessary in optical lithography. We must also evaluate and develop RET without allowing present restrictions to slow us. Two restrictions are that a very severe accuracy of alignment is required for the projection lens and that a practical non-linear sensitive resist has not yet been obtained.

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