Subwavelength Lithography (PSM,OPC)

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Abstract - Fabrication of fine features of smaller 0.15um is vital for future ultra-large scale integrated (ULSI) devices. An area of particular concern is whether and how optical lithography can delineate such feature sizes, i.e., smaller than the exposure wavelength. Resolution enhancement techniques for achieving subwavelength optical lithography are presented. Various types of phase shift mask (PSM) techniques and their imaging characteristics are discussed and compared to conventional binary mask technique. To apply these masks effectively to practical patterns, optical proximity effect correction (OPC) technique and a phase shifter pattern design tool must be established. These techniques offer the capability to improve resolution to exceed the wavelength limitation and to increase depth of focus.

I. INTRODUCTION

Optical lithography is widely used for mass-production of ultra large-scale integrated (ULSI) devices because its superiority in economic terms. The minimum feature size required for fabrication of ULSI has decreased as ULSI packing density has increased. To improve the resolution of the optical lithography, the use of shorter wavelength exposure light and large numerical aperture of projection exposure lens have been investigated. At present, 0.25-um patterns can be fabricated using KrF(wavelength=248nm) excimer laser light. However, minimum feature size of most advanced ULSI devices is much smaller than exposure wavelength. The critical issue is how to improve the resolution with high reliability for fabricating small features without decreasing the depth of focus.

In this paper, the characteristics of lithographic technologies will be reviewed and resolution enhancement techniques in optical lithography will be discussed. These resolution enhancement technologies include phase shift mask techniques [1-4], off-axis illumination [5,6], pupil filtering techniques [7-8], and associated approaches. These techniques enable optical lithography tools to fabricate fine features and will lead to further miniaturization of ULSI devices.

II. REQUIREMENT FOR LITHOGRAPHY TECHNIQUES

The trend of minimum feature sizes of ULSI devices and lithographic performances is shown in Fig. 1. The integration level has increased fourfold every two or three year. Because advances in optics and resist materials, optical lithography is still the most important lithographic technologies in the industrial environment. However, the minimum feature size of ULSI devices becomes smaller than wavelength of exposure light used in the optical system. In fact, 64M bit DRAMs have been developed with a minimum feature size of 0.19um which is smaller than exposure wavelength of KrF excimer laser light (0.248um).

Ways to obtain high resolution and better alignment accuracy with minimal increase in cost and minimal reduction in throughput are needed. Besides the resolution enhanced optical lithography technique, electron beam (EB) lithography and the combination of EB and optical technologies have a chance to play important roles in the mass-production of ULSI devices. X-ray lithography is also an option because they are considered an extension of present optical lithography using extremely short wavelength. These technologies have not been used much in industry, though, because their throughput is lower than optical technique and equipment cost is high.

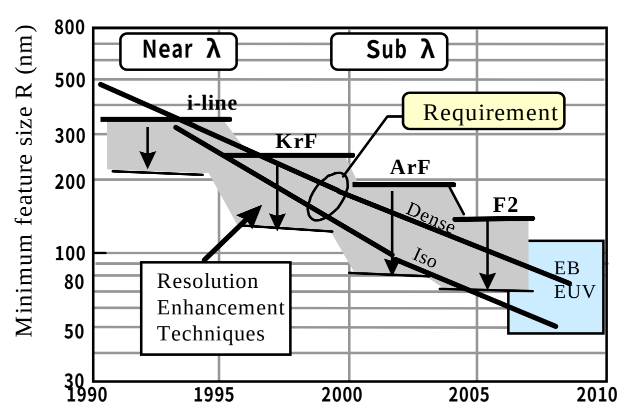

Fig. 1 Lithography requirement and development trend of lithographic technologies.

III. RESOLUTION LIMIT OF OPTICAL LITHOGRAPHY

The schematic design of a typical optical exposure tool is shown in Fig. 2. The tool consists of a light source, a condenser, a stage for mask at the object plane, a projection lens with very small wavefront aberration, and a stage for the wafer. At each point on the wafer, light converges with a corn of half angle of θ. The numerical aperture of the projection lens is defined as NA=sin θ . In this optical exposure system, the smallest feature R that such optical system can project and the depth of focus DOF which is the range over which the image remains in adequate focus are important issues. They are expressed by these familiar expressions as

$$R=k_1 \lambda/NA \quad (1)$$

$$DOF=k_2 \lambda/NA^2, \quad (2)$$

where λ is the exposure wavelength, and k_1 and k_2 are process dependent constants. According to the Rayleigh's criteria, the values of k_1 and k_2 are 0.6 and 0.5 respectively.

Using the shorter wavelength exposure light permits one to project features of the same size with low value of NA and thus with a large DOF. Current exposure wavelength is 248 nm from the KrF laser, and shorter wavelengths are available such as 193 nm from the ArF laser and 157 nm from the F2 laser. Exposure lens design with NA of larger than 0.65 is also available today for obtaining high resolution R. A continuation of the shorter-wavelength and large-NA strategy encounter tremendous difficulties such as optical materials and photoresist transparency. Under these circumstances, resolution enhancement techniques such as phase shift mask (PSM) techniques have been reconsidered.

IV. RESOLUTION ENHANCED OPTICAL LITHOGRAPHY

The concepts of increasing resolution of optical lithography are summarized in Fig. 3. In the exposure tool, the mask is illuminated by light from the light source, and

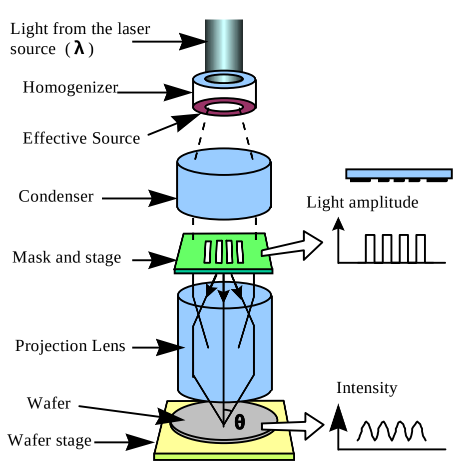

Fig. 2 Essential elements of exposure optics.

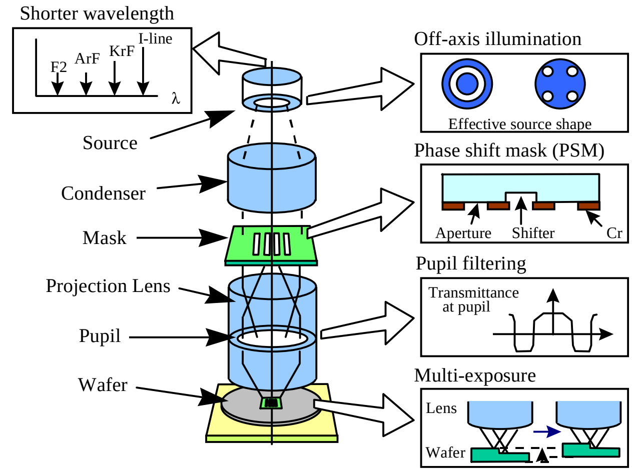

Fig. 3 Schematic structure of exposure optics and resolution enhancement techniques.

patterns on the mask are projected onto the wafer surface through the projection exposure lens. Resolution enhancement is achieved by modifying the source shape, by using special mask that introduce a phase difference, or by placing a filter at the pupil plane of exposure lens. Other methods such as multi-exposure method to align multi-focal level, and surface imaging process for low optical constant condition have also been proposed.

A. *Phase shift mask*

A phase shift mask (PSM) utilizes not only the light intensity distribution used in conventional masks but also the optical phase. Figure 4 compares the working of an alternate-type PSM with a conventional binary mask. To create the 180 degree phase difference of light passing through adjacent apertures on the PSM, the mask surface has non-planar structure. The depth of the trench d shown in Fig. 4 is given by

$$d= \lambda /\{2(n-1)\} \quad (3)$$

where n is the index of refraction of transparent mask substrate.

Here, we consider the periodic patterns, i.e., the higher order diffraction components are eliminated. Let the period of intensity transmittance be $1/\nu_0$ near the diffraction limit, then the amplitude transmittance T(x) of the phase shift mask and binary mask are

$$\text{Phase shift mask: } T(x)=\cos(2\pi\nu_0 x) \quad (4)$$

$$\text{Binary mask: } T(x)=|\cos(2\pi\nu_0 x)|, \quad (5)$$

where x is a coordinate on the image plane. The PSM gives Fourier components at $\nu=-\nu_0/2$ and $\nu_0/2$, while the binary mask gives at $\nu=-\nu_0$, 0, and ν_0 as shown in Fig. 4. The

exposure lens is considered to be a spatial filter that transmit components of less than critical frequency ν_C(=NA/λ). Therefore, when $\nu_C < \nu_0 < 2\nu_C$, the binary mask does not give an image because of the elimination of fundamental components, while the PSM can form a pattern image because the fundamental components transmit through the exposure lens. This is a concept of improving resolution under coherent condition (incoherence ratio σ=0) and gives the largest effect among the many kinds PSMs. In practice, an incoherence ratio σ of 0.3-0.5 is used. An increase in image contrast by using PSM is illustrated in Fig. 5. This PSM technique offers k_1 value of smaller than 0.35 in Eq. (2), while its value is around 0.5. Experimental results of delineating 0.13-0.15um patterns are shown in Fig. 6 which correspond to k_1=0.29-0.33.
for binary mask.

Although the alternate-type PSM has the great advantage of increasing the resolution of periodic patterns, it can not be easily applied to random patterns. To overcome this pattern restriction, several algorithms for automatic shifter layout designs [9-11] and methods of using plural masks to superpose their images [12,13] have been developed.
Besides the alternate-type PSM, several types of PSM concepts have been proposed as shown in Fig. 7. The attenuate-type (halftone) PSM consists of a glass substrate and the attenuated layer. Weak light passes through the attenuated region, but its intensity is insufficient to develop the photoresist on the wafer. The attenuated region acts as the phase-shifted region with respect to the main apertures. Although the attenuate-type PSM does not improve resolution as well as the alternate-type PSM, they can easily applied to isolated patterns such as holes and random patterns. Out-rigger and RIM type PSM which have additional narrow phase shifting apertures have also been proposed to enable PSMs to be applied to the fabrication of isolated patterns. The phase-edge design is a kind of strong PSM, which corresponds to the alternate-type PSM with very narrow or none opaque region. Since the optical phase changes suddenly at the shifter edge, a very narrow dark line image is obtained and the image size exceeds the resolution limit of periodic line patterns. This mask technique will be partially applied to fabricate gate patterns.

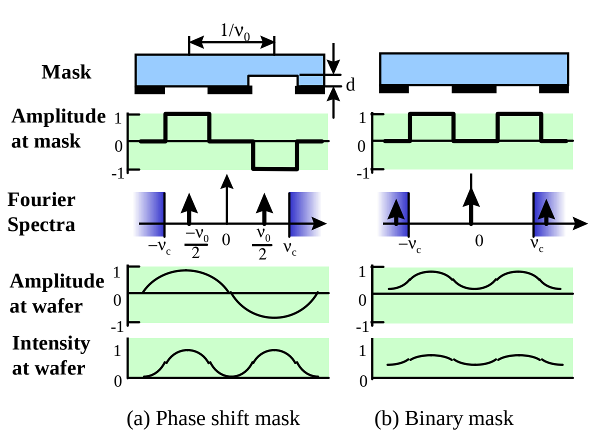

Fig. 4 Concept of (a) alternate-type phase shift mask and its optics compared with (b) a conventional binary mask

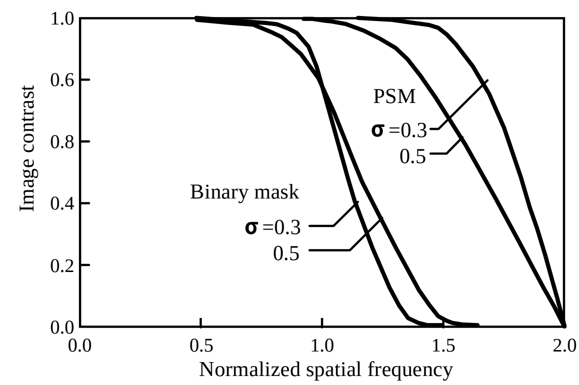

Fig. 5 Increase in projected image contrast by using PSM for periodic line patterns.

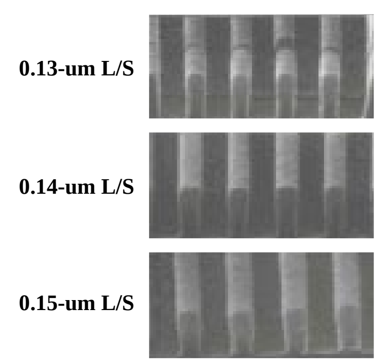

Fig. 6 Improved resolution achieved with a PSM (KrF, NA=0.55, σ=0.3)

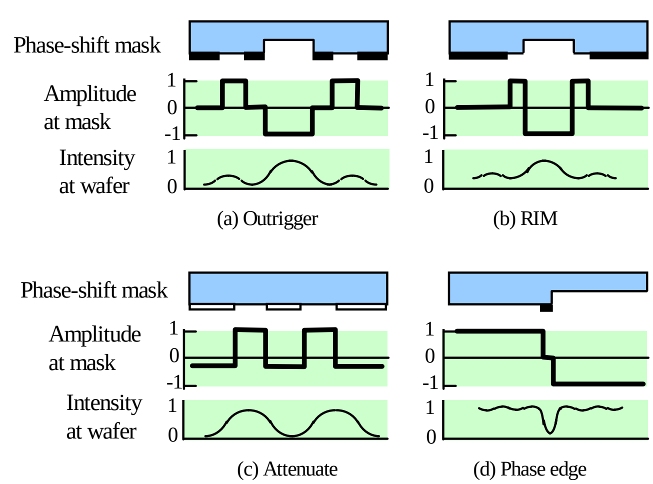

Fig. 7 Several types of PSM and their images.

B. Off axis illumination and pupil filtering techniques

High resolution can also be obtained by changing the illumination conditions. An off-axis illumination technique uses oblique illumination created by decreasing the intensity at the center region of the source as shown in Fig. 8. In the conventional illumination method, the zeroth-order diffracted light (the undiffracted beam) enters the lens along to the optical axis and the first-order light enters with a diffracted angle. As the linewidth on the mask becomes small, the angle becomes large. When this angle becomes larger than the acceptable one of the exposure lens, the image contrast becomes zero. In the case of off-axis illumination, however, two beams such as zeroth and remaining first-order diffracted light can transmit the lens and interfere at the wafer plane to produce an image in a manner of analogous to the operation of the PSM.

To implement this technique in exposure tools, modified light source shapes have been proposed as shown in Fig. 9. The annular shape is a basic arrangement and provides a moderate effect. The quadrupole shape has a strong effect to improve resolution similar to an alternate-type PSM technique. While the quadrupole illumination improves the performance of x and y geometries on binary masks, it has a strong directionality and provide poor resolution for mask features oriented at 45 degree. Because the zeroth-order beam is stronger than the first-order beam, perfect interference and 100% image contrast are not possible with off-axis illumination and binary masks. But, the mask designs required do not suffer from the mask making with phase topology problem.

Maintaining the DOF is also an important issue in optical lithography. A technique for increasing practical DOF was first introduced as the FLEX method [14] for isolated window patterns. This is based on the multiple exposures and superposition of light intensity for different focal planes.

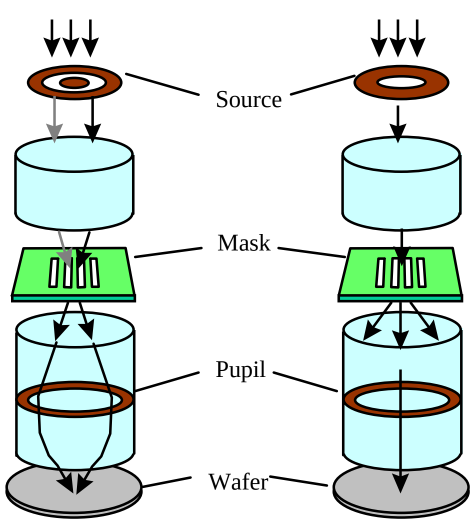

Fig. 8 Off-axis illumination method using oblique illumination compared with normal illumination method.

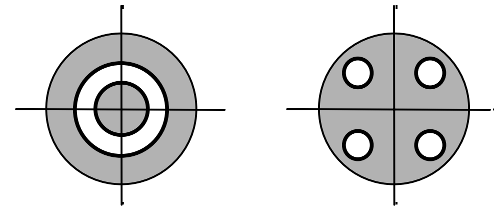

Fig. 9 Examples of light source shapes for the off-axis illumination method.

On the other hand, a pupil filtering technique [7] can superpose the light amplitude. Such superposition is achieved by placing a special filter at the pupil plane of exposure lens. Multiple pupil filtering image superposition technique was also demonstrated [8], and fine isolated lines corresponding to k_1=0.2 were fabricated.

C. Optical proximity effect correction technique

Using the strong PSM and the exposure tool with a numerical aperture (NA) of around 0.7, fine patterns with the size of approximately a half of the exposure wavelength can now be formed. In such subwavelength patterning, however, pattern fidelity to images on the wafer drops due to the optical proximity effects. One of the methods to compensate for this deterioration is to modify the shapes of mask patterns so that they will produce desired aerial images on the wafer as shown in Fig. 10. This pattern modification method is called as optical proximity correction (OPC). In Fig. 10, small patterns called as serif are added at the corners of main patterns to increase the fidelity to images. This processes need to be automated for practical use of OPC. Rule-based and simulation-based approaches are needed in the subwavelength lithography. A verification of the validity of such modifications before making masks is also important. The mask design tool which have functions including image calculation, phase shifter placement and sidelobe overlap checking for attenuate PSM has been reported [15].

V. PROBLEMS WITH R.E.T. FOR PRACTICAL USE

Although various types of resolution enhancement technologies provide the great effects of increasing resolution, they also tend to emphasize the effects of residual aberrations in the projection exposure lens on the projected images. Spherical and coma aberrations are most critical for imaging characteristics. In particular, coma gives an image placement error depending on the pattern shape, size, pitch, and illumination condition. The simulated image shifts depending on the spatial frequency and illumination conditions are shown in Fig. 11. Assuming a little large coma aberration of 0.2λ, an image positional shifts of 20nm to 60nm is observed.

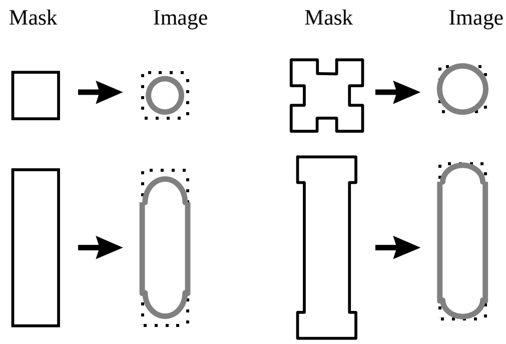

Fig. 10 Optical proximity effects and their correction by modifying the shapes of mask patterns.

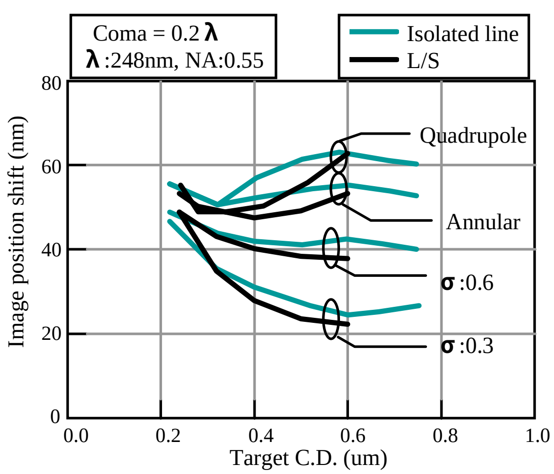

Fig. 11 Simulated image positional shifts due to the aberration depending on pattern size and illumination condition.

Since various pattern size and illuminations are adopted in the actual device fabrication processes, those image shifts due to the aberrations cause a deterioration of overlay accuracy. Therefore, residual aberrations in optical system must be decreased to overcome this overlay error problem.

Since the PSM consists of normal chrome patterns and phase shifter patterns, its manufacturing process is more complicated than a conventional mask. Both the phase shifters and chrome patterns are expected to be defect-free. As far as defect detection is concerned, the conventional defect detection method or con-focal optical microscope system is available. However, complete mask repair method has not established yet. The usefulness of the PSM surely depends on the mask fabrication and defect repair technologies.

VI. CONCLUSIONS

Many types of resolution enhancement technologies, in particular PSM techniques, are looked at and their imaging characteristics are discussed. The use of a PSM with the current high NA projection exposure tool gives us the potential to form fine features with less than exposure wavelength. Effective use of these technologies will extend the practical resolution limit of optical lithography.

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