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Resolution limits of optical lithography

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The development of optical lithography has promoted the development of ultralarge scale integration (ULSI) devices. However, optical lithography is now facing serious obstacles due to the limitations in wavelength. Higher resolution with sufficient depth of focus is the most important requirement for ULSI engineers. To satisfy this requirement, many technologies for resolution improvement and new optical image formation technologies such as phase shifting and focus latitude enhancement exposure (FLEX) are reviewed, and a future perspective on optical lithography is also discussed in this paper.

I. INTRODUCTION

The development of ultralarge scale integration (ULSI) devices has been very rapid. Concerning the dynamic random access memory (DRAM) device, a fourfold higher integration level has been achieved every 2 to 3 years.[1] Microfabrication technology, especially lithography technology has promoted this development.[2] Among the various lithographic technologies, optical lithography plays an important role in the industrial environment.

More than 10 years ago, the resolution limit of optical lithography was thought to be 1–2 μm. At that time, there was skepticism that optical lithography could be used for the fabrication of submicron ULSI devices. Nevertheless, optical lithography has been used for not only submicron ULSI fabrication but also for half-micron ULSI fabrication. However, optical lithography is now facing serious obstacles due to the limitation of wavelength.

The minimum feature size of the most advanced ULSI devices is almost the same as the exposure wavelength.[3–5] To continue using optical lithography, therefore, we must introduce a much shorter wavelength light or some new ideas to overcome the wavelength limitation. As a result, resolution capability and maintenance of adequate depth of focus are important issues to be tackled in optical lithography.

In this paper, recent activities on obtaining higher resolution with adequate depth of focus are reviewed and a future perspective on optical lithography is discussed.

II. DEVELOPMENT OF THE OPTICAL SYSTEM

The resolution limitation in optical lithography is basically dependent on the well known Rayleigh's equation. The resolution R and the corresponding depth of focus (DOF) are given by the following equations:

$$R = k_1 \times \lambda / \mathrm{NA},$$

$$\mathrm{DOF} = k_2 \times \lambda / \mathrm{NA}^2.$$

Here λ is the exposure wavelength, and NA is the numerical aperture of the lens system. Constants k_1 and k_2 are dependent on resist materials, process technologies, and image formation technologies.

From these equations, it can be seen that a higher NA and a shorter λ contribute to a higher resolution. Stepper manufacturers have been extensively making efforts to develop higher NA lens systems. Recently, they have also been trying to develop a lens system for shorter wavelength light.

Figure 1 shows the evolution of developments in optical lithography. Not only the development in optics, but also many innovations have been introduced for the resolution improvement. Figure 2 shows the evolution of developments regarding lens systems. As the required resolution was 1.5–2 μm at the beginning of the development (early 1980s), a *g*-line (436 nm) lens system having a small NA value was developed.

Due to the requirements for higher resolution, new lens systems with higher NA were developed in the middle of the 1980s. The required resolution was reduced to the 1 μm level. The NA of these lens systems was at about 0.45, and the depth of focus of them was wider than $\pm 1.5\ \mu$m.

Submicron patterns were required in the late 1980s. To achieve these patterns, 0.5 or higher NA lens systems were needed without shortening the wavelength. The depth of focus of the lens systems having such a high NA value was reduced to within $\pm 1.0\ \mu$m. Then, many innovative ideas for process and resist materials were introduced.[6–12]

Such smaller depth of focus also restricted the choice of device structure. The selection of the memory cell structure for DRAMs was heavily dependent on the depth of focus of

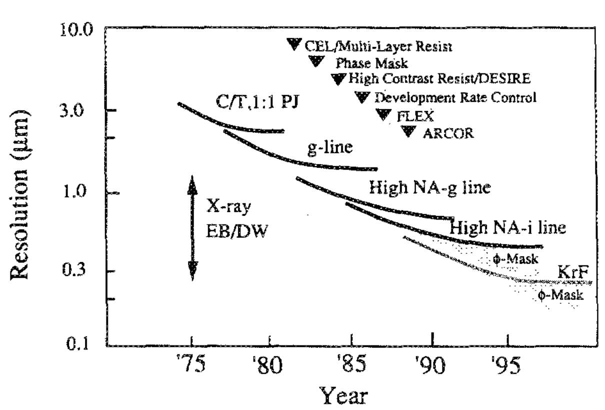

FIG. 1. Evolution of developments in optical lithography.

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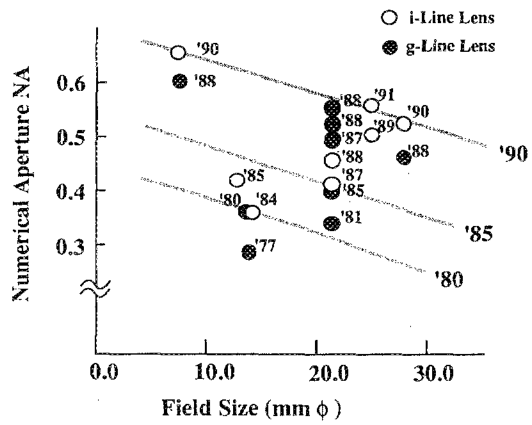

FIG. 2. Evolution of developments regarding lens systems.

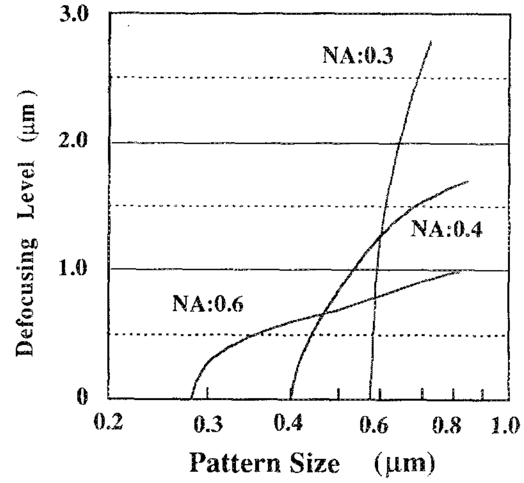

FIG. 3. Relationship between defocusing level and resolution capability for various numerical aperture lens systems.

the lens system. As the surface topography of trench capacitor cells is relatively small, smaller depth of focus lens systems could be used. On the contrary, as the stacked capacitor cell structure needed a larger depth of focus, higher NA lens systems could not be used.

To overcome this problem, the use of shorter wavelength light was attempted. In place of *g*-line light, *i*-line (365 nm) light from a mercury lamp was adopted. By using *i*-line light, the lens system having a NA of 0.4 could be used for the delineation of submicron patterns. Almost the same depth of focus as the former *g*-line lens systems could be maintained by these of *i*-line exposure.

From the beginning of the 1990s, half-micron pattern delineation was required for the fabrication of 16 Mb DRAMs. Higher NA lens systems applying *i*-line exposure brought smaller depth of focus. Much shorter wavelength light such as KrF excimer laser light has become the candidate for the next light source.[13] Several experimental lens systems were already developed.

III. PRACTICAL RESOLUTION (REFS. 14 AND 15)

From an industrial point of view, higher resolution with adequate depth of focus is required for lens systems. Figure 3 shows the relationships between defocusing level and resolution capability for various numerical aperture lens systems. On the focal plane, a higher resolution can be obtained by a higher NA lens system as Rayleigh's equation predicts.

However, under a somewhat defocused condition, a higher NA lens system will not always give higher resolution capability. For example, at 1 μm defocus condition, the lens system with 0.3 NA gives a higher resolution than the lens system with 0.6 NA as shown in Fig. 3. This means that the resolution capability of the projection lens system is limited by the defocusing condition.

According to the increase in the NA value, the depth of focus decreases rapidly. At a certain NA value, the depth of focus equals the required depth of focus. This NA value is the optimum NA value which gives the highest resolution satisfying the required depth of focus. The lens system having a NA higher than this optimum NA gives a lower resolution at the acquired depth of focus.

The resolution satisfying a certain depth of focus value will be referred as a practical resolution in this paper. Figure 4 shows the relationships between practical resolution and NA. As shown in this figure, the resolution minimum and the NA value which gives the minimum resolution change with the required depth of focus. A smaller required depth of focus will give a higher resolution at higher NA value.

These relationships are also affected by the applied process technology and wavelength. Figure 5 shows the dependence on wavelength. Shorter wavelength lights have smaller optimum NA values. This means that the minimum practical resolution can not be proportional to the reduction ratio of the wavelength.

IV. NEW IMAGE FORMATION TECHNOLOGY (REFS. 16 AND 17)

As far as the use of *i*-line exposure, to maintain $\pm 1\ \mu$m depth of focus, the minimum resolution cannot be smaller than 0.5 μm. On the other hand, the use of a shorter wavelength light enables a smaller practical resolution. However,

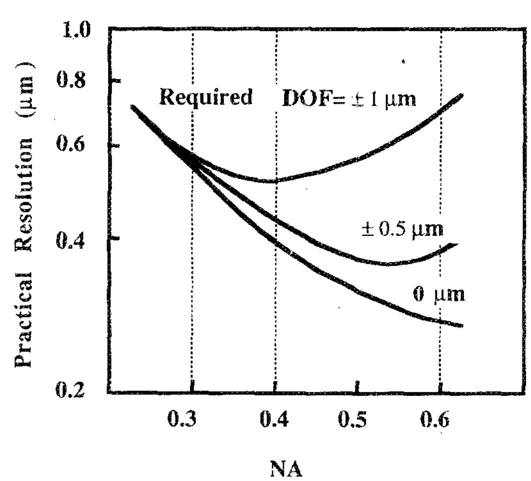

FIG. 4. NA dependence of practical resolution.

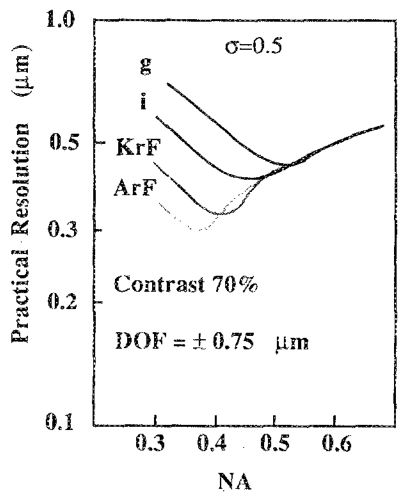

FIG. 5. Effect of exposure wavelength change on practical resolution for line and space patterns.

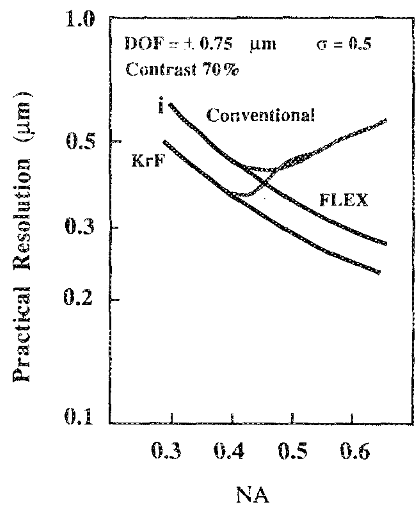

FIG. 7. Effects of FLEX on practical resolution improvements for hole patterns.

there are many problems that must be solved before a shorter wavelength light can be used.

To obtain higher resolution with sufficient depth of focus, new image formation technologies have been investigated. Phase shifting method[16] and focus latitude enhancement exposure (FLEX) method[17] are examples of these new technologies. The FLEX method uses the superposition of several exposures with changing focusing conditions. The phase shifting method uses not only the intensity profiles of the images but also the phase information of the images.

Figure 6 shows the basic concept of the FLEX method. This method is very effective on the isolated transparent pattern, because it superposes several images with changing focusing conditions. The defocused images of isolated transparent patterns have very small light intensity contrasts; consequently, the superposed images are almost the same as sharply focused images.

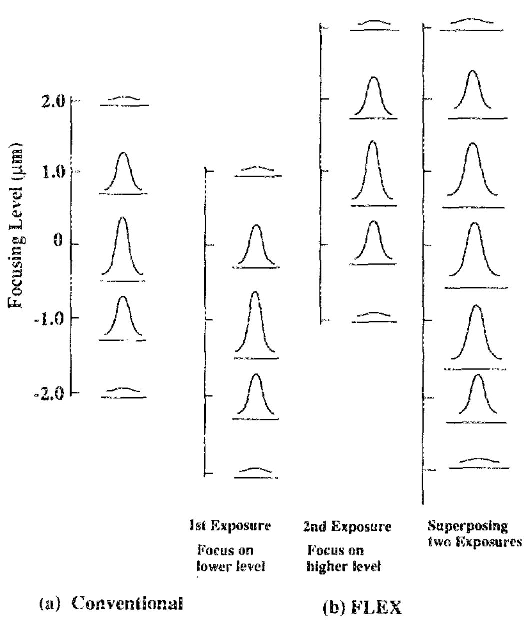

FIG. 6. Basic idea of FLEX. FLEX (*F*ocus *L*atitude enhancement *EX*posure).

By using FLEX, higher resolution can be obtained with higher NA lens system having a larger depth of focus. Almost the same resolution predicted by Rayleigh's equation can be obtained with the large depth of focus as shown in Fig. 7.

Figure 8 shows the basic concept of the phase shifting method. By introducing phase change between adjacent images, the light intensity between these images can be cancelled. Then images closely projected can be separated completely. From this basic idea, it can be seen that the phase shifting method is very effective on periodically repeated patterns such as line and space patterns.

Using the phase shifting method, a higher resolution will be obtained with larger depth of focus as shown in Fig. 9. In this method higher coherency value is suitable for the illumination.

As shown in the basic idea, the biggest problem with the phase shifting method is the restriction of pattern layout. The phase shifting method can be easily applied to periodical patterns; however, it is very difficult to apply this method to random patterns.

To overcome this problem, several modified methods of using phase change for pattern formation were investigated. The use of subshifter pattern for isolated pattern formation is one of the examples.[18] Arranging a phase shifting area around opaque pattern in another example. This method is called the edge-enhanced-type phase shifting method.[19]

The edge of the shifter itself can be a narrow opaque pattern. A narrow shifter pattern has two closely located edges. Each of these edges creates opaque patterns. Using this pattern formation technique, very high resolution patterns are expected. Figure 10 shows the simulated results. Assuming shorter wavelength exposure and high NA lens system, very

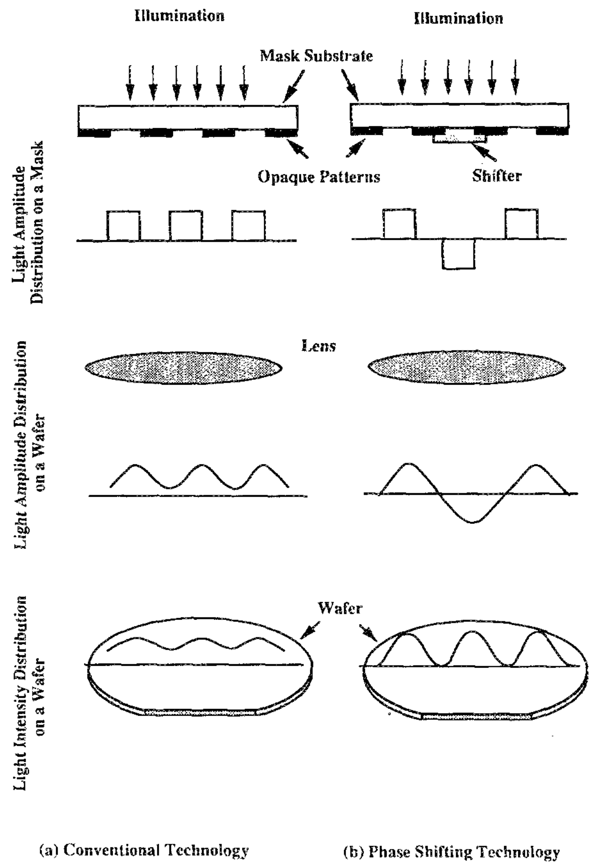

FIG. 8. Basic idea of phase shifting method.

high contrast light intensity profile of 0.15 μm line and space pattern can be expected.

V. SUMMARY

Optical lithography has been widely used for fabricating LSI devices for a long time. However, optical lithography is now facing a resolution limitation due to the wavelength.

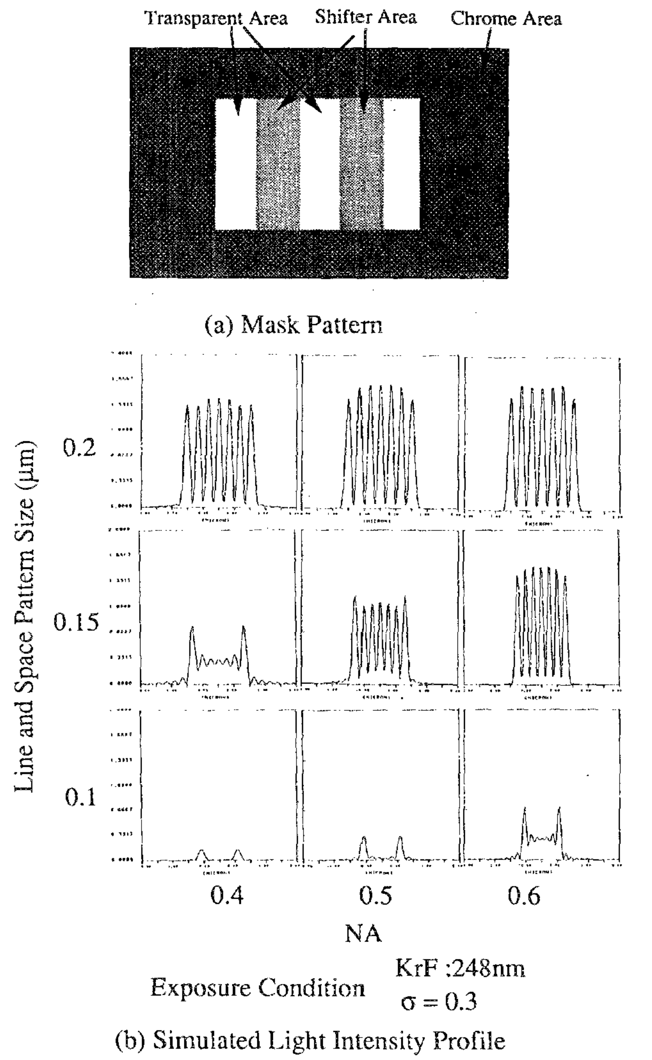

FIG. 10. High resolution line and space pattern delineation capability using shifter edge: (a) plain view of mask pattern; (b) simulated light intensity profiles.

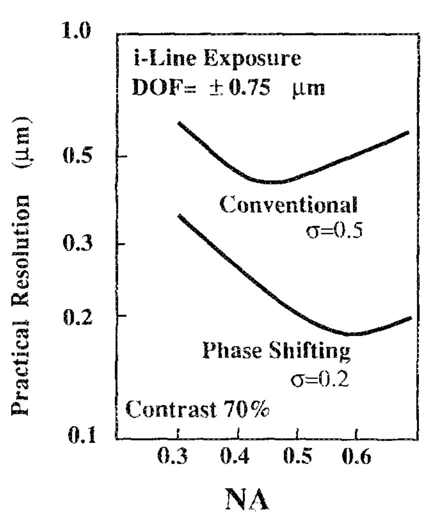

FIG. 9. Effect of phase shifting method on practical resolution improvements for line and space patterns.

The use of a shorter wavelength light will be one solution in the future; however, there are currently no practical instruments, no good resist materials and no advanced process for shorter wavelength light. Therefore some new ideas are required to obtain higher resolution with sufficient depth of focus using conventional exposure wavelength.

Phase shifting method and FLEX method will be candidates for overcoming the obstacles. Using the FLEX method and the phase shifting method, 0.3 μm or smaller pattern size with sufficient depth of focus can be obtained. Applying these ideas to excimer laser light exposure, 0.2 μm or smaller pattern can also be delineated.

The resolution limit of optical lithography has been renewed many times. More than 10 years ago, it was believed the limitation was 2 μm. Now by applying phase shifting, it will no longer be difficult to achieve 0.2 μm. I believe that 0.1 μm or smaller pattern will be delineated by optical lithography in the near future.

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