

The Recent Progress of Lithography Machine and the State-of-art Facilities

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Abstract. With the rapid development of industrial intelligent manufacturing and electronic information technology, the importance of integrated circuits has grown fast. Photolithography, as the core technology of integrated circuit industry, has become a key research target for researchers all over the world. In this paper, we provide a brief introduction to photolithography as well as an outlook on the future development direction. Firstly, the key metric of lithography system, which is resolution, and how it relates to lithographic performance is analyzed. Secondly, some exposure methods developed on UV and DUV light sources are discussed, which are commonly used in the industry nowadays. Subsequently, this paper presents the structure and performance of some representative lithography equipment. Then, some summarizations are completed about the most recent advances in EUV lithography and high NA lithography. Finally, we examine the limitations of current lithography and forecast the future of lithography. The goal of this paper is to provide a guide on lithography equipment, particularly the most advanced products available nowadays. Additionally, some potential challenges that photolithography may face in its future development are highlighted, and some perspectives on how photolithography will evolve over the next decade are provided. These results shed light on guiding the future development direction of lithography machine as well as ways to push Moore's law even further.

Keywords: Integrated Circuit Industry, Lithography Equipment, High-NA EUV Lithography Machine, Step-and-scan System, Light Source.

1. Introduction

In 1965, Moore postulated that the number of transistors that can be packed into a given unit of space will double about every two years [1], which become an important law on semiconductor industry development so called Moore's law. As time goes by, the whole semiconductor industry still develops under the guidance of Moore's law. Lithography, a core technology of semiconductor industry which determines whether Moore's law continue to be effective. In the development of lithography machine, on exposure style, lithography machine started at contact aligner, via proximity aligner, projection lithography machine, stepper, step scan lithography machine, immersion lithography machine and to now extreme ultraviolet (EUV) lithography machine. On exposure light source, researchers keep on exploring how to apply shorter wavelength light on the lithography machine to manufacture smaller circuit on chip. Firstly, blue light with a wavelength of 436 nanometers (nm) emitted by the mercury lamp was used as the source in lithography machine in 1980s, which can achieve 1 micrometer critical dimension. Afterwards, wavelength of source came to 365 nm, known as the mercury i-line, pushed feature sizes reaching 220 nm. In the mid-1980s, laser started to use, the lithography got in Deep Ultraviolet (DUV) period. The Deep Ultraviolet lithography (DUVL) started to play a more and more important role in the semiconductor industry. ArF excimer laser with 193 nm wavelength and KrF excimer laser with wavelength of 248 nm were been widely used in industry as exposure light source [2]. F₂ excimer laser can provide light with a wavelength of 157 nm, but by 2003, 157 nm was written off as an impractical next step in optical lithography after 193 nm for limitation on photoresist and mask material [3]. Later, 193 nm immersion lithography took place of 157 nm lithography by introducing an immersion fluid with a refractive

index >1 [4]. Immersion lithography brought projection optics with numerical aperture (NA) over 1. The NXT:2050i produced by Advanced Semiconductor Material Lithography (ASML) company is the most advanced DUV lithography machine using immersion lithography technology with 1.35 NA and can achieve resolutions down to 38 nm.

Although DUVL machine can make linewidth down to 7-5 nm by using multiple exposure technique, but if we want to get tinier linewidth, DUVL reached its limit. The Extreme Ultraviolet lithography (EUVL) applying EUV as light source which light with a wavelength of 13.5 nm becomes the focus of the study. ASML's EUVL machine NXE:3600D can reaches 13 nm resolution, with 5-3 nm logic nodes manufacture capacity. As next generation lithography, ASML and Carl Zeiss are developing a high-NA EUV exposure system with NA = 0.55 [5].

In this paper, we give an overview of lithography machine and introduce facing challenge. The rest part of the paper is organized as follows. The Sec. 2 will give a brief introduction about basic principles of lithography machine, like the Rayleigh criterion and some relationship between parameters and lithography machine performance. The Sec. 3 will introduce different types of lithography machine. The Sec. 4 will show the advanced EUV lithography machine and the high-NA EUV lithography machine more focus on light source and optic. The Sec. 5 will analyze the limitations of lithography machine research or technology problem and give a future prospect.

2. Principle

2.1 Resolution

Since the invention of integrated circuit in 1958, the integration density of integrated circuit has been increasing, and the feature size has also been decreasing. Until now, the linewidth of integrated circuit pattern has been reduced by about five orders of magnitude, and processing techniques with linewidth of 28 nm ~ 45 nm are very common now. Meanwhile, the integration density has increased by more than seven orders of magnitude, and an integrated circuit chip can now contain tens or even hundreds of millions of devices. These accomplishments are largely due to advances in lithography. Lithography with a linewidth of less than 1 μm is already technically complex, and further reducing the lithographic pattern size on this basis would present a number of technical or even theoretical challenges. At the moment, the primary issue to be solved is how to improve the resolution of lithography even further.

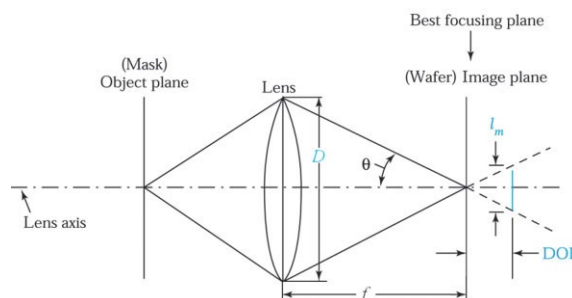


Figure 1. Simple image system [9].

Resolution describes the ability of an imaging system to resolve detail, in the object that is being imaged [6]. The smallest size of a line that can be distinguished and processed by a lithography system or the area that can be adequately printed by a machine is called the minimum resolution for micrographic processing. Resolution is one of the most important metrics for a lithography system. The higher the resolution, the smaller the linewidth that a lithography system can resolve. The Rayleigh criterion equation can be used to determine resolution.

$$l_m = \frac{k_1 \lambda}{NA} \quad (1)$$

where l_m is the critical dimension, or the smallest possible feature size. λ is the wavelength of the light that be used. k_1 is a coefficient that depends on many other factors related to the chip manufacturing process. k_1 is generally equal to 0.75, and the physical limit lithography is $k_1 = 0.25$

[7]. NA is the numerical aperture of the optics, generally in the range of 0.16 to 0.9. NA defines how much light they can collect, and is given by

$$NA = \bar{n} \sin \theta = \bar{n} \sin \left(\tan^{-1} \frac{D}{2f} \right) \approx \bar{n} \left(\frac{D}{2f} \right) \quad (2)$$

with \bar{n} is the refraction index in the image medium (usually air, where $\bar{n} = 1$), θ is the half-angle of the cone of light converging to a point image at the wafer, D represents for the diameter of the lens and f is the focal length [8], as shown in Figure 1 [9]. According to Eq. (1), the resolution can be improved by lowering the wavelength λ (where the limit of lithographic processing is $\lambda/2$, i.e., half-wavelength resolution), increasing NA , optimizing the system design (resolution enhancement techniques), and lowering k_1 .

2.2 UV Exposure

Ultraviolet (UV) and deep ultraviolet (DUV) light sources are now widely used as exposure light sources in industry. The most common exposure methods using UV and DUV light sources are contact printing, proximity printing, and projection printing, as illustrated in Figure 2 [10].

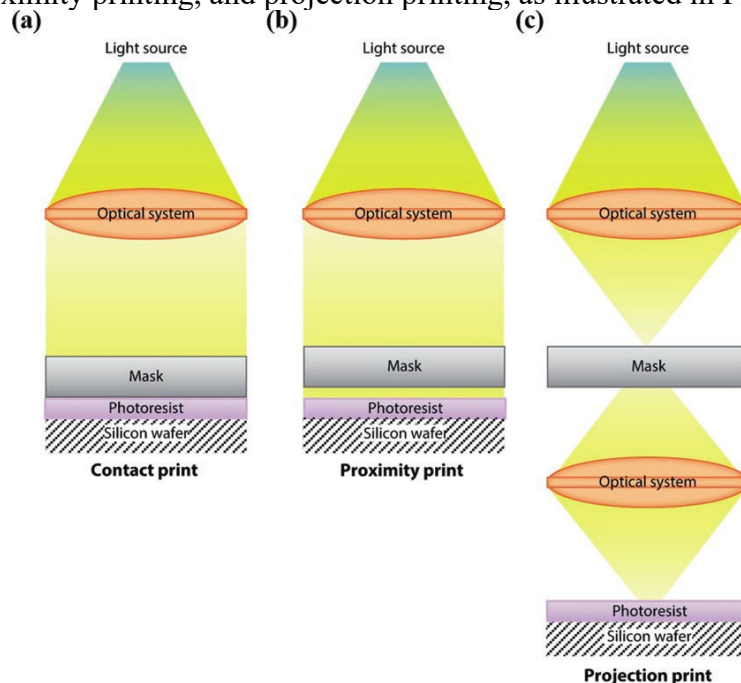


Figure 2. Schematic diagram of photolithography. (a) Contact printing, (b) proximity printing, and (c) projection printing [10].

2.2.1 Contact printing

As shown in Figure 2a [10], the resist-coated silicon wafer makes physical contact with the mask in this technique. The wafer is held in place by a vacuum system. When the wafer comes into contact with the mask, the system is exposed to UV light from the mask's top, and the exposure process takes place in the photoresist layer. Contact printing can achieve high resolution and is superior to proximity printing because the photoresist and the mask are in direct contact [11]. It was the first method of exposure used in integrated circuit research and production, but it is now obsolete due to the disadvantage that dust trapped between the photoresist. Besides, the mask can damage the mask and cause pattern defects, resulting in a lower yield. Furthermore, it cannot be reused since the mask is in direct contact with the photoresist [11].

2.2.2 Proximity printing

Proximity printing is similar to contact printing. Figure 3 gives the proximity printing system's schematic diagram [11]. It is made up of four major components: a light source and optical focusing system, a mask, a silicon wafer, and an alignment table. The optical focusing system converts the UV

light emitted by the mercury lamp into parallel light, and the parallel light passes through the mask and forms the image of the pattern on the photoresist. Since there is a small gap s between the mask and the silicon wafer (typically $s = 5 \mu\text{m}$), this method is referred to proximity printing. Theoretically, the resolution of lithography is $1/\lambda$. However, in proximity printing system, there is a small gap s between the mask and the silicon wafer, so there will be some limitations on resolution because of diffraction. In reality, proximity printing can only be used in processes above $3 \mu\text{m}$.

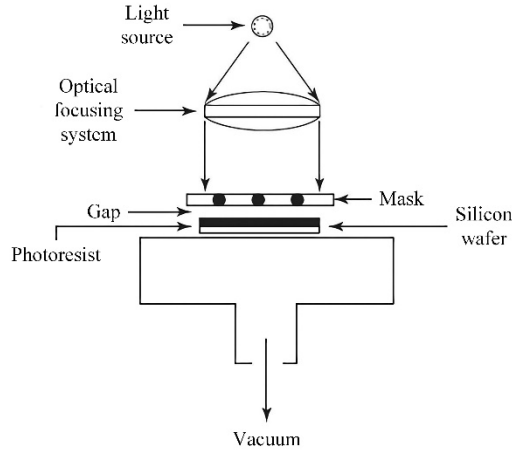


Figure 3. Proximity printing [11].

2.2.3 Projection printing

Figure 4 shows a schematic diagram of the projection printing system [11]. An optical focusing system converts the light emitted by the light source into parallel light, which then passes through the mask and is projected on the wafer by a second optical focusing system. There is an alignment system between the wafer holder and the mask. Actually, only a small portion of the mask is imaged in order to achieve high resolution in projection printing. This small region image field is scanned over the surface of the wafer. Projection printers that step the mask image over the wafer surface with a resolution of several nanometers are called step-and-repeat systems [11]. The projection printing system's resolution is primarily limited by diffraction, and in general, projection printing can reach submicron levels.

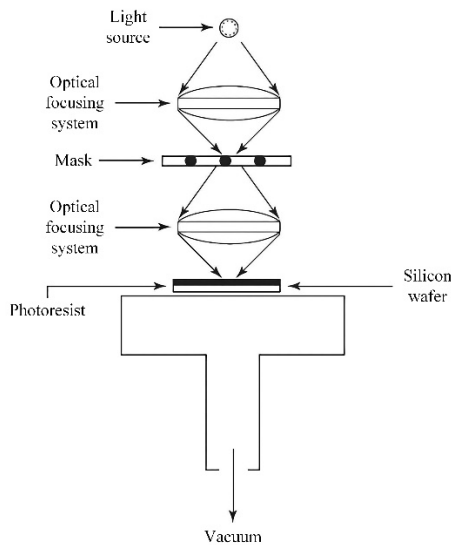


Figure 4. Projection printing [11].

Projection printing has two most significant advantages. One is that the silicon wafer does not come into contact with the mask, so process defects due to abrasion caused by contact are eliminated. The other is that the mask is not easy to break, so it can be carefully corrected to remove defects, thus improving utilization of the mask. Because of these advantages, projection printing has emerged as one of the most important methods of lithography less than $3 \mu\text{m}$ processes.

3. Lithography equipment

There have been five generations of lithography equipment since the invention of the planar process, and each generation is represented by a type of equipment that is able to reach a certain critical dimension (CD) and resolution. The five lithographic eras are represented by contact aligner, proximity aligner, scanning projection aligner, step-and-repeat aligner, and step-and-scan system.

3.1 Contact aligner

From the SSI era to the 1970s, contact aligner was the primary method of lithography. It was used in manufacturing processes with linewidth of 5 μm and above. Although 0.4 μm linewidth can also be achieved, contact aligner is no longer widely used contemporarily. Figure 5 exhibits the schematic diagram of contact aligner system [12]. The mask of the contact aligner contains all of array patterns that will be copied to the surface of silicon wafer. The silicon wafer is coated with photoresist and is loaded onto a stage that can be controlled manually. The mask and the silicon wafer are viewed simultaneously through a microscope with split vision, and then operator manually positions the stage to align the patterns on the mask with the patterns on the silicon wafer. Once the mask and the silicon wafer are aligned, the mask makes direct contact with the photoresist coating on the wafer's surface, which is why this equipment is known as contact aligner. The mask and the wafer are then exposed to ultraviolet (UV) light. UV light passes through the transparent part of the mask, then the patterns on the mask are transferred to the photoresist.

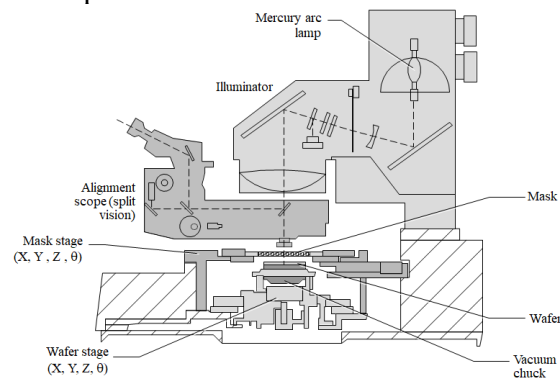


Figure 5. Schematic diagram of contact aligner system [12].

3.2 Proximity aligner

Proximity aligner evolved from contact aligner and was widely used in the 1970s, during both the SSI and early MSI era. However, these aligners are still used in some labs with low-volume production or some old wafer lines which produce discrete devices, because it is not cost effective for them to invest in replacing old equipment with new one. In actual manufacturing, this type of equipment is appropriate for processes with linewidth of 2 to 4 μm .

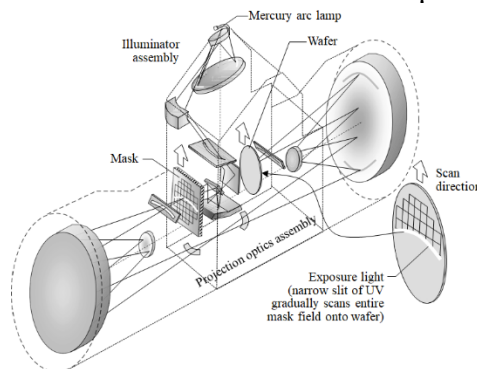


Figure 6. Scanning projection aligner [14].

3.3 Scanning projection aligner

In the early 1970s, the development of scanning projection aligner (also known as scanner) attempted to solve the previously mentioned problems of contact aligner and proximity aligner. In the late 1970s and early 1980s, scanning projection aligner was the dominant lithography exposure tool [13]. These aligners are still used in old wafer lines with linewidth greater than 1 μm . The idea behind scanning projection aligner is to use a reflection system to project the entire pattern on the mask with a 1:1 image onto the surface of silicon wafer. Because the mask is 1X size, the image is not scaled, and the pattern on the mask is the same size as the pattern on the silicon wafer. As illustrated in Figure 6 [14], UV light is focused on the silicon wafer via a slit to obtain a more uniform light. The mask and the photoresist-coated wafer are placed on a scanning shelf and move in unison, then the photoresist on the wafer is exposed by the narrow UV beam. The image on the mask is eventually copied exactly to the wafer surface as a result of the scanning motion.

3.4 Step-and-repeat aligner (Stepper)

Step-and-repeat aligner, also known as stepper, was the mainstream lithography equipment used for silicon wafer fabrication in the 1990s. Step-and-repeat aligner gets its name from the fact that this equipment can only project one exposure field at a time (which could be one or more chips on the silicon wafer), and then steps to the next location on the wafer for the next exposure. Stepper dominated the IC manufacturing industry in the late 1980s [15]. It was primarily used to form patterns with critical dimensions as small as 0.35 μm (conventional i-line photoresist) and 0.25 μm (deep UV photoresist) [16]. Instead of a mask, stepper employs reticle owing to the fact that a reticle contains patterns in a single exposure field corresponding to one or more dies, whereas a mask includes all die arrays. The optical projection exposure system of a stepper projects the reticle image onto the silicon wafer using refractive optics. A step-and-repeat aligner is represented in Figure 7 [12].

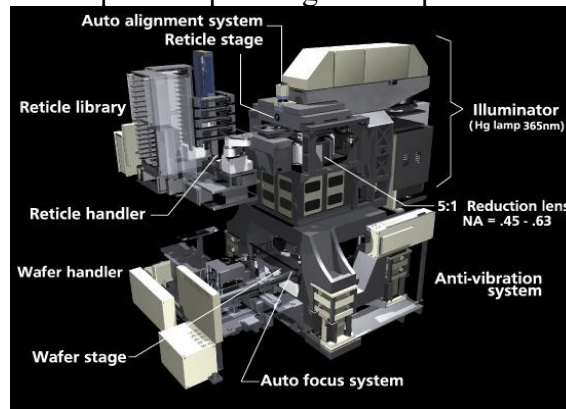


Figure 7. Step-and-repeat aligner (Stepper) [12].

Yield is the main issue with stepper. While scanning projection aligner can produce nearly 100 wafers per hour, stepper typically produces only 20 to 50 wafers per hour. Eq. (3) can be used to express the output of a system

$$T = \frac{1}{O + n \times [E + M + S + A + F]} \quad (3)$$

Here, n represents the number of dies on each wafer, E represents the exposure time, M represents the time of the stage's movement for each exposure, S represents the stabilization time of the stage, A represents the field-by-field alignment time (if used), F represents the autofocus time (if used), and O represents the time including loading/unloading, pre-alignment, moving wafers in and out of the system, and performing global alignment. To reduce or eliminate O , some of the items in total time can be completed concurrently with the exposure of previous wafer. Because n is typically between 50 and 100, the total time in parentheses in Eq. (3) is critical to a stepper's commercial success. As a tool that can be used practically, it should be kept to 2 or less.

3.5 Step-and-scan system

To resolve the conflict between the size of exposure field and the cost of lens, development in lithography exposure equipment resulted in the emergence of a new technology known as step-and-scan system. Step-and-scan system is a hybrid device that combines scanning projection aligner technology and step-and-repeat aligner technology. It uses a reduced lens to scan the image of a large exposure field onto a portion of the silicon wafer. Both the reticle and the silicon wafer are swept by a narrow band of focused light. The standard size of exposure field for a step-and-scan system is 26 mm×33 mm, and a 6-inch reticle is used, as depicted in Figure 8 [17]. When the scanning process and pattern transfer process are finished, the wafer is stepped to the next exposure area and the scanning process is repeated.

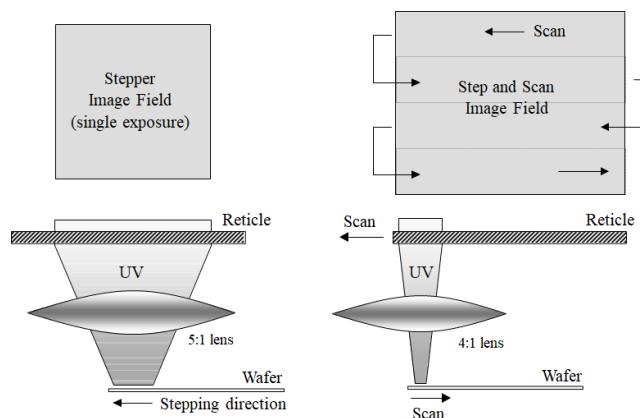


Figure 8. Wafer exposure field for step-and-scan system [17].

The use of step-and-scan system to expose silicon wafers has the advantage of increasing the exposure field, resulting in larger chip sizes. The field of the lens can just be a thin strip shape, as the full-wafer scanning projection aligner. Before stepping to the next position, it scans a reduced reticle (typically 4X) through a small and well-corrected 26 mm×33 mm image field [13], which is schematically illustrated in Figure 9 [17]. Another significant advantage of the wider field is that more patterns can be placed on the reticle, allowing for more dies to be exposed in a single exposure.

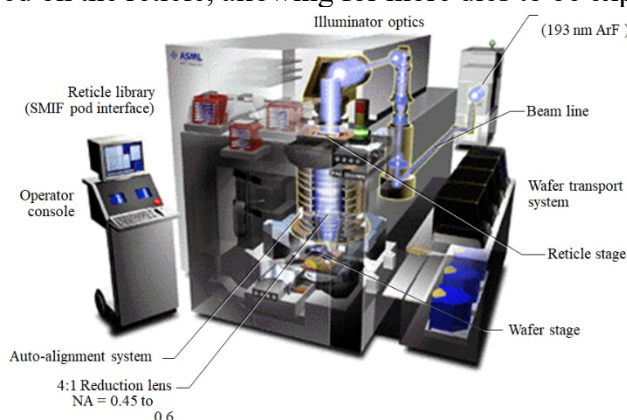


Figure 9. Step-and-scan system [17].

Table 1. Methods of exposure and widely used time of each generation of lithography equipment.

Lithography equipment	Exposure method	Widely used time
Contact Aligner	Shadow printing	During the SSI era until the early 1970s
Proximity Aligner	Shadow printing	During the SSI and early MSI era
Scanning Projection Aligner	Projection printing	In the late 1970s and early 1980s
Step-and-repeat Aligner (Stepper)	Projection printing	Since the late 1980s
Step-and-scan System	Projection printing	Nowadays

Furthermore, step-and-scan system also has the ability to adjust focus throughout a scanning process to compensate for lens defects and variations in wafer flatness. This improves the control of

focus during the scanning process, which results in a better control of CD uniformity throughout the exposure field. The main challenge for step-and-scan system is the increased requirement for mechanical tolerance control, as the motion of the wafer stage and the reticle stage must be controlled synchronously. A stepper only needs to move the wafer quickly to a new position, but a step-and-scan system must move the wafer and the reticle simultaneously and precisely in opposite directions. Positioning tolerances cannot exceed tens of nanometers during the scanning and stepping processes. Table 1 summarizes the methods of exposure employed by each generation of lithography equipment and the time periods during which they were widely used.

4. State-of-art products

4.1 EUV lithography machine

EUV lithography machine is the most advanced lithography machine in semiconductor industry being widely used to manufacture below 7 even 5 nm process chip. The core system of the whole machine is the exposure system. It creates the EUV light. The system must be vacuumed to prevent absorption of EUV by substances in the air to get a high efficiency. The Laser-produced plasma (LPP) source uses Sn droplet and the CO₂ laser to create 13.5 nm EUV light as shown in Figure 10 [18]. When a Sn droplet have left the generator, it will be 'conditioned' by pre-pulse. The Sn target after optimizing has lower density than a liquid target, so that more Sn ions are involved to emit EUV leading to higher conversion efficiency [19]. A EUV source power of 250 W has been realized [20]. Higher power of EUV source means higher throughput. For lens, high reflectivity mirrors are used in exposure system will be absorbed when it penetrates lens attributed to the EUV light, which will cause efficiency down. To guaranteed the transmission efficiency, multilayer coating on the mirrors which basically acts as a Bragg reflector [21]. ASML's advanced EUV lithography machine is NXE:3600D, using 13.5nm wavelength EUV light and have 13nm resolution. The 3600D can be used to make 5 and 3nm logic nodes and leading-edge DRAM nodes. The projection optics of them are 0.33NA. As for productivity, it can throughput larger than and equal 160 wafers per hour at a dose of 30 mJ/cm².

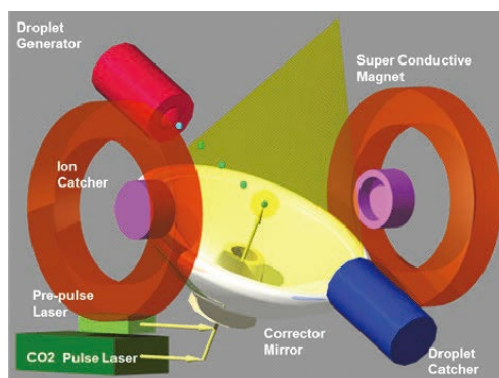


Figure 10. Schematic of LPP EUV light source [18].

4.2 High-NA EUV lithography machine

ASML and Carl Zeiss are developing a next-generation EUV exposure system with NA = 0.55 [22]. Comparing with the 0.33NA lithography machine, NA improve 67% to provide sub-8-nm half-pitch resolution [23]. For light source, the LPP source still be used, but power of light source which is applying on the EUV lithography machine is not enough to print smaller patterning. To achieve 10 nm half-pitch patterning, doses should larger than 80 mJ/cm² [24]. Throughput will low significantly if power of light source is too low. A 500 W source with 80 mJ/cm² dose will produce 120 wafers per hour for a high-NA EUV lithography machine. The limit of mechanical considerations is 185 wafers per hour in case the light source power is high enough. This limitation will happen when power of light source reach 1.3 kW or higher with 80 mJ/cm² doses [25].

The Increasing NA will spell larger deflection angle and large mirrors. As the last mirror of high-NA optical system, the angle of light cone will be increase from 19° to 33° contrasting the EUV lithography machine on the basis of relation $NA = n \sin \alpha$. For the penultimate mirror, to avoid the block of the last mirror, the deflection angle should be increased and the mirror will be larger. The multiple coating on mirror acts as the Bragg reflector, which must be work at the deflection angle and can get maximum reflectivity if the angular variation as small as possible. To address the issue about how light illuminate the last mirror with smaller deflection angles. ASML introduces a central obscuration as is shown in Figure 11 [26]. To the mask side, NA will also be increased will system NA increasing. The inject light and reflect light will overlap in transmission. An anamorphic 4x/8x system was decided to avoid the contrast loss. But the exposure field will decrease to half than past [27, 28]. Figure 12 demonstrates some other improvements of high-NA lithography machine comparing the 0.33-NA lithography machine [29].

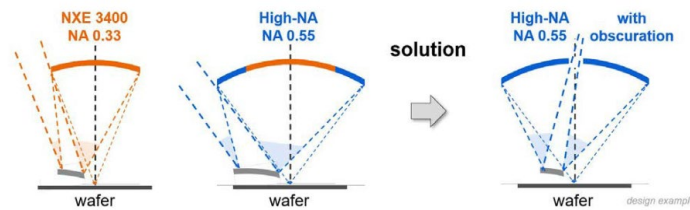


Figure 11. Decreasing incidence angle by introducing central obscuration [26].

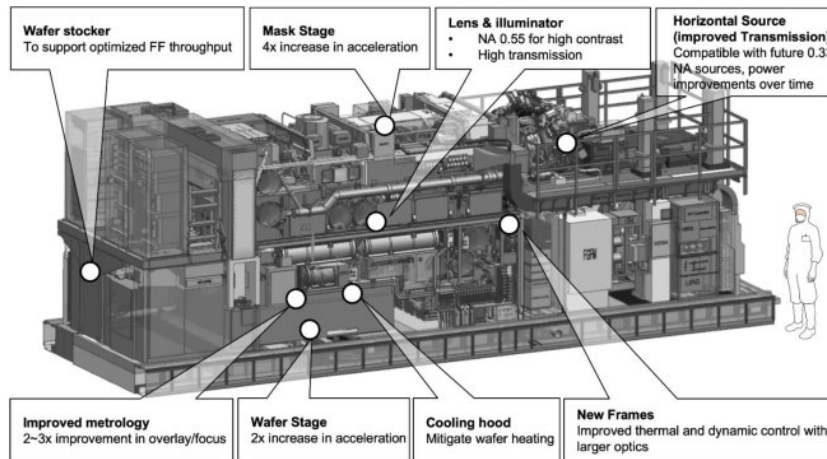


Figure 12. Differences between EUV lithography system and high-NA lithography system [29].

5. Limitations & Future prospects

With guidance under Rayleigh criterion, it is available to find light with a shorter wavelength, increase NA and get closer to the k_1 limit. Considering wavelength of EUV lithography light source is 13.5 nm, almost reach the real x-ray wavelength range. The loss of x-ray will very high for x-ray is too penetrating to reflection material on mirrors of EUV lithography machine and will cause low efficiency. On the other hand, x-ray light source means higher power demand which will bring in new problem on electric power supply. Finding another light with shorter wavelength is more difficult than increase the NA. The alternative way increasing NA is related to the depth of focus (DoF). According to the formular of DoF,

$$DoF = k_2 \frac{\lambda}{NA^2} \quad (4)$$

where k_2 is a factor related to process. DoF will decrease as NA goes up. When $k_2=1$, the DoF will be approximately 45 nm which is about 1/3 comparing with 120 nm DoF of the EUV lithography machine. In order to hide the off-focus in the Airy disc, the DoF control should better than 35 nm [20]. Lower DoF will bring in new challenge to flatness of wafer surface, thickness of photoresist and new requirements for system control. Large NA will cause the aperture of mirror higher and make the mirror larger and heavier also becoming an unignorable problem, giving more difficulty to

manufacturing and assembling. To the central obscuration, diffraction and part of the diffraction spot of order 0 or even order 1st diffraction spot will be shadowed [30], i.e., lost some information of pattern cause blurry.

Lithography machine is an extreme complex and precise system. To break the technology limit, we should consider the way to apply shorter wavelength light source and reduce loss of light with short wavelength in transit under guidance of Rayleigh criterion. In terms of light source, free-electron laser (FEL) is an alternative way to generate light which is suitable for lithography. FEL has some advantages e.g., continuously adjustable wavelength range, high output power, high quality light beam. The EUV FEL and the XFEL have huge potential on generating light can be used on lithography machine. Nevertheless, the device used to generate FEL is quite huge and expensive. The path to miniaturize FEL device and apply it in industry remains a research hotspot. If FEL can be applied in the lithography industry, higher power and shorter wavelength will bring in improvement of productivity and finer patterns. In addition to the light source, optimize the optical reflection system is necessary to make a more compact structure and save cost. Trying best to increase NA may be an easier way than find a light with shorter wavelength. If wavelength of light and the NA is limited, adjusting k_1 to demonstrate the best performance is worthy to consideration. High-NA lithography is a strong tool extending the Moore's law, but the challenge that one should face is not only the mechanical limitation but also the physical limitation with the lithography machine development.

6. Conclusion

In summary, this paper discusses features about lithography machine from the prospective of light source and transmission system. Specifically, general introduction to lithography machine is given primarily. Then, the resolution, a key metric of lithography system, as well as some common exposure methods developed on UV and DUV light sources are discussed. Afterwards, for each generation of lithography, this paper presents a representative lithography equipment. Subsequently, we also summarize features about EUV lithography machine and the advanced development of high-NA lithography machine. At last, this paper analyzes the limitations of the state-of-art lithography machines and outline the future prospects. Lithography is the key to extend Moore's law, while high-NA lithography machine broadens the Moore's law to the next decade. With a view to the future, it is necessary to consider feasible approach in the next era of lithography to address the problem of physical limitations before us. Overall, these results offer a guideline for lithography machines, especially the state-of-art products, while putting forward some points of view, pointing out some potential challenges on development of lithography machine and coming up with solutions accordingly.

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