The influence of excimer laser performance on lithography

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Abstract: The excimer laser light source can bring smaller image resolution and more uniform exposure pattern to the lithography machine. At present, excimer lasers have been used in 7 nm lithography process and are becoming perfect, which brings lower operation cost, higher yield and throughput, thus promoting the development of the whole semiconductor manufacturing industry. This paper first reviews the basic principle of excimer laser lithography, investigates the influence of excimer laser light source on lithographic imaging, then elaborates on the monitoring technology of excimer laser light source at present stage and looks forward to the future development of excimer laser.

Key words: excimer laser light source, lithography, energy and dose, wavelength and bandwidth.

1. Introduction

With the continuous development of semiconductor technology, the improvement of precision and efficiency of lithography as one of its core links has received increasing attention. Among them, the application of ArF laser light source in the field of lithography is particularly prominent, and its high power, high stability and environmental protection make it an important tool for future semiconductor manufacturing. However, how to optimize ArF laser light source to meet the manufacturing needs of higher resolution and larger area is the focus of current research. On the one hand, researchers are exploring the design and optimization of new ArF lasers to achieve higher power output and wider working wavelength range[1-5]. For example, by improving the injection locking mechanism of the laser, a high power output of 6kHz can be achieved; by introducing new optical designs, manufacturing with smaller process can be realized. On the other hand, researchers are also paying attention to the impact of ArF laser light source on the lithography process, including the influence of laser bandwidth, light source polarization, beam quality and other factors on lithographic performance[6-12]. Figure 4 shows how the light source parameters affect the key exposure dimensions from lens aberration, focusing, dose control, optical proximity effects, and lighting. These studies help us better understand and control the lithography process, thereby improving the performance of semiconductor processes. This review will comprehensively sort out the research progress on the application of ArF laser light source in lithography technology and its influencing factors, aiming to provide a systematic reference framework for researchers in related fields and look forward to future research directions.

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Parameters	Impact
E95 bandwidth	Contrast, CD control
E95 bandwidth target	
FWHM bandwidth	
Energy average	Dose control
Energy sigma	
Wavelength sigma	Overlay, focus
Wavelength target	
Time stamp	Event correlation
Beam pointing	Illumination stability, contrast, system matching, troubleshooting (scanner vs. laser)
Beam divergence	
Beam size	
Beam energy density	
Polarization	
Metrology integrity configurables	Data integrity
Module pulse counts	Maintenance flagging

NEW METROLOGY

Figure 1. The measured light source parameters and its impact.

2. The main models of excimer laser sources in lithography

In the field of photolithography, the current mainstream excimer laser light sources are the 193 nm ArF laser and the 248 nm KrF laser. The 157 nm F2 light source has not gained mainstream acceptance due to factors such as its high replacement cost for photoresists and lens materials. KrF represents the first-generation excimer light source employed in photolithography, owing to its significant advantages in terms of output energy, wavelength precision, linewidth, stability, and other critical factors, surpassing earlier mercury lamp light sources. Concurrently, as the semiconductor industry and photolithography technology continue to advance under the influence of Moore's Law, the emergence of ArF light source technology with shorter laser wavelength radiation has become evident. With continuous iterations and improvements in KrF and ArF light sources, the photolithography nodes have progressed steadily. Table 1 provides information on various models from companies such as ASML, Nikon, Canon, and their respective light source parameters (where NA denotes numerical aperture).

Table 1. Some models of lithography systems for ASML, Nikon and Canon, and laser sources of these systems

Company	Model	Exposure type	Resolution /nm	Laser source	NA	Output rate (Wafer /h)
ASML	NXT1980Di	Immersion step-and-scan exposure	38	193 nm ArF	1.35	275
	XT1450H	Dry step-and-scan exposure	65	248 nm KrF	0.93	180
	PAS5500/850D	step-and-scan exposure	110	248 nm KrF	0.80	145
Nikon	NSR-S631E	Immersion step-and-scan exposure	38	193 nm ArF	1.35	1.35
	NSR-S322F	step-and-scan exposure	65	248 nm KrF	0.92	270
	NSR-S210D	step-and-scan exposure	110	248 nm KrF	0.86	230
Canon	FPA-6300ES6a	step-and-scan exposure	90	248 nm KrF	0.86	200

Key parameters for photolithography machines encompass resolution, numerical aperture, overlay error, and throughput, among others. The resolution of a photolithography machine reflects its ability to project the smallest image clearly and is directly linked to the capabilities of the excimer light source. According to the Rayleigh criterion, photolithography resolution can be expressed as follows:

$R = K_1 * (\lambda/NA)$

where R represents the resolution, K_1 denotes the process constant, λ stands for the center wavelength of the light source, and NA refers to the numerical aperture. K1 is intertwined with photoresist processes, illumination coherence, and wavefront control. Enhancing the photolithography node from the light source perspective primarily involves optimizing the wavelength, energy, spectral width, and stability of the light source. Critical dimensions and overlay errors are significantly influenced by light source parameters. Principal parameters of excimer laser light sources encompass repetition rate, average power, bandwidth (inclusive of 95% energy integral (E95) and full-width at half-maximum (FWHM)), bandwidth stability, center wavelength, center wavelength stability, dose accuracy, single-pulse energy and stability, beam position stability, and beam pointing stability, among others. The assessment of excimer laser light sources for photolithography adheres to a rigorous set of measurement, calculation, and evaluation criteria, necessitating mutual recognition by light source and photolithography machine manufacturers.

3. Light Source Main Parameters and Their Impact on Photolithography

In the realm of photolithography, meeting the requirements of semiconductor photolithography process nodes necessitates fundamental research aimed at enhancing the performance metrics of the corresponding lithographic nodes. As the semiconductor nodes continue to shrink, the future performance of excimer lasers primarily hinges on the stability of their light source parameters. The successful adoption of techniques like double exposure and multiple exposure in photolithography processes has introduced more stringent demands on process control. These include critical dimensions, overlay errors, edge placement errors, photomasks, and reticle tools, all of which require additional methods to address errors while maintaining a robust process. Additionally, the light source needs to be closely integrated and adjusted with the back-end photolithography process to optimize critical dimensions, overlay errors, and edge placement errors by reducing various light source parameters, as illustrated in the diagram. Therefore, research into these light source parameters becomes essential.

3.1. Center Wavelength and Bandwidth

Ideally, excimer laser outputs should be monochromatic, meaning the output beam has only one single wavelength ($\lambda 0$) that remains fixed and stable in both spatial and temporal domains. However, in reality, due to technological limitations, it is challenging to produce laser sources that emit perfectly monochromatic light. The goal is to minimize the bandwidth of excimer lasers, which can be considered as the finite oscillation around the center wavelength.

From fundamental optical principles, wavelength variations can lead to changes in the imaging focal plane. Ideally, these changes must be kept as close to zero as possible. In practical manufacturing, lenses used for DUV immersion lithography exhibit chromatic aberration, which means that small wavelength shifts can result in significant changes in focus, primarily due to chromatic aberration (defined as the longitudinal change of focus or image position with respect to wavelength). Within the limited bandwidth, image formation is the result of the superimposition of the image intensity contributed by each wavelength, leading to a blurred imaging plane. The degree of this blur is directly proportional to the wavelength range being sampled. Consequently, the laser bandwidth significantly impacts critical performance metrics in various photolithography techniques, including process windows, CD uniformity, MEEF, OPC effectiveness, and others.

In addition to wavelength, the key optical parameter used to characterize an excimer light source for DUV lithography is the bandwidth, which can be represented using two different metrics: Full-Width-Half-Maximum (FWHM) and E95. FWHM conveys a general representation of the light source spectrum and its changes at half intensity, but it cannot describe the complete spectral shape. The other metric, instead, is based on the 95% integral energy(E95) of the spectrum, and therefore can be used as a single metric to represent the shape of the spectrum. In the semiconductor industry, E95 is widely consider the most reliable metric for the ArF light sources used in lithography applications. Figure 2 shows the difference between FWHM and E95.

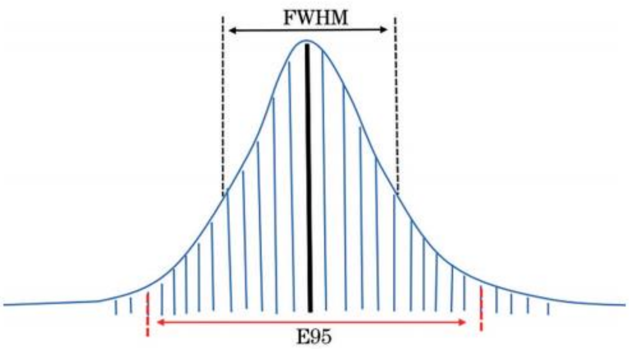

Figure 2. Diagram of E95 and FWHM.

Smaller semiconductor nodes require improved linewidth stability and wavelength stability. The stability of E95 is directly proportional to the consistency of critical dimensions. To achieve smaller critical dimensions, it is essential to enhance bandwidth stability. Simultaneously, wavelength stability affects overlay error and focus. Further optimization of overlay error and focus relies on the subsequent validation within the illumination and objective systems of the light source.

The stability of parameters such as wavelength and linewidth not only directly impacts the absolute values of critical dimensions and their consistency in exposure patterns but also plays a significant role in reducing imaging blur caused by chromatic aberration, especially when combined with optical proximity effect correction. This leads to improved image contrast. Moreover, in cases of collaborative optimization between the light source and the photomask, enhancing the E95 metric can improve exposure tolerance, enhance mask error enhancement factor, and enhance the consistency of critical dimensions.

3.2. Beam Performance

Polarized light plays a crucial role in photolithography, particularly in high numerical aperture (NA) projection lithography and immersion lithography. Polarized light can influence the propagation, scattering, and absorption of light, thereby affecting resolution, depth, and alignment accuracy in the photolithographic process. As technology advances and process nodes continue to shrink, the impact of polarized light on photolithography becomes increasingly significant. Optimizing polarized illumination has become a vital research direction in computational lithography. Employing polarized illumination enhances the imaging quality in photolithography, enlarging the process window. Reference 10 has shown that different polarization lighting methods can have different effects on DOF, as shown in Figure 3.

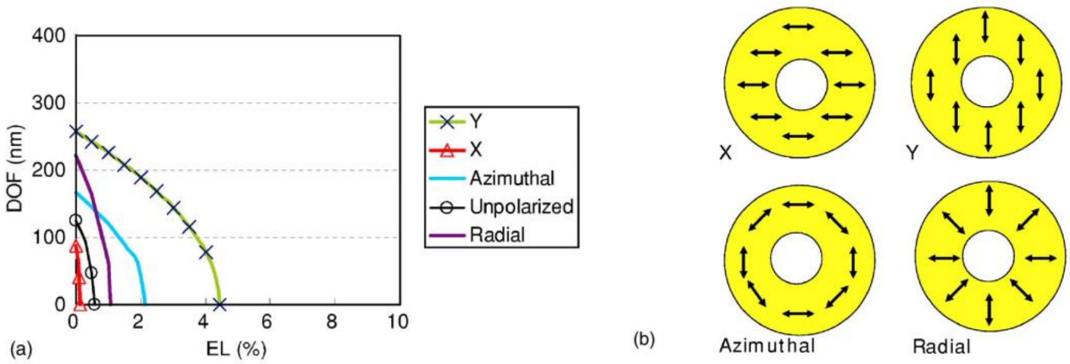

Figure 3. (a) EL-DOF window difference between polarizations under the annular illumination (att-PSM). (b) Definition of polarization in y-parallel LS pattern.

Divergence is generally used to describe the size of the light source's output beam. Changes in the divergence of the output beam can occur due to factors such as aging of the internal optical components of the light source. Literature indicates that variations in beam divergence angle can lead to changes in energy distribution, thereby affecting the critical dimensions (CD) after exposure. Figure

4 shows the laser output light source divergence and beam size

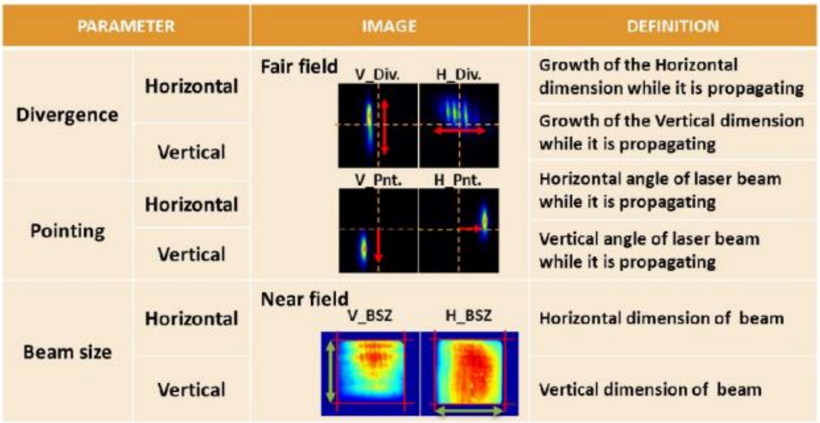

Figure 4. Divergence and beam size.

3.3 Pulse Energy and Dose Stability

The quality of pulse energy stability directly impacts dose stability, and improving dose stability can reduce photolithography errors. In the context of semiconductor photolithography, the concept of energy variation, known as "energy sigma," is of paramount importance. Energy sigma represents the standard deviation of the average pulse energy over a sequence of pulses and is typically expected to be within 3% to 4%, with even lower values being ideal. Control of pulse energy relies first on precise regulation of the discharge voltage, with a requirement for single-pulse voltage accuracy to be maintained within 0.5‰. Furthermore, sophisticated energy control algorithms are employed to manage "energy sigma" or dose stability effectively.

4. Photolithography Process Optimization Techniques

Photolithography process monitoring is a critical step in semiconductor manufacturing, involving precise measurement and control of the performance parameters of the light source to ensure high-quality patterns during the photolithography process. As integrated circuit technology continues to advance, the demand for smaller, faster, and more efficient photolithography techniques has increased significantly, making monitoring and control of the light source even more crucial. To meet these demands, researchers have developed various advanced photolithography process monitoring techniques and methods[13-18].

The fundamental principle of photolithography process monitoring involves real-time monitoring of changes in performance parameters of the light source that can impact photolithography and providing timely feedback. For example, companies like Cymer have developed on-board monitoring systems that allow end-users to detect changes in the spatial and far-field profiles of each exposure chip, as well as changes in polarization performance. These technologies also characterize pattern effects resulting from variations in the control of optical parameters of the light source. Gigaphoton has similarly developed Fault Detection & Classification (FDC) monitoring systems that provide light source performance data to the FDC system during exposure time. This system offers essential monitoring data, such as energy, wavelength, bandwidth, and beam performance data, including beam profile, pointing, divergence, and polarization.

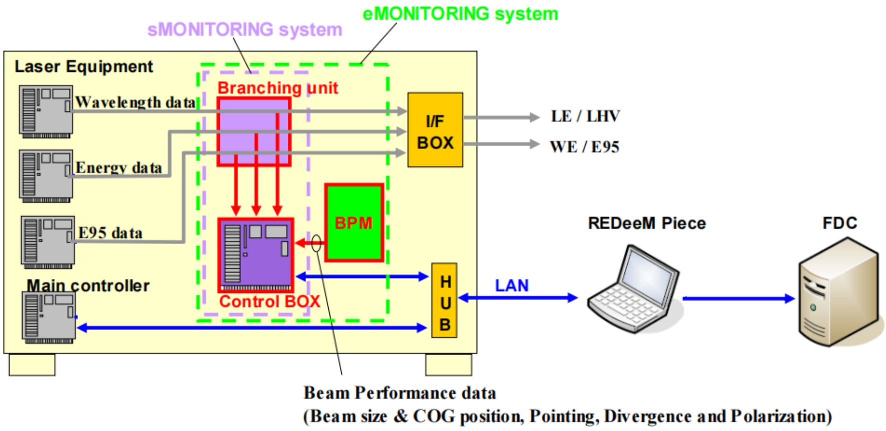

Figure 5. FDC system overview diagram.

5. Conclusion

In conclusion, excimer lasers, serving as light sources for advanced immersion photolithography machines in semiconductor manufacturing, have been the focus of continuous performance enhancement by light source manufacturers. By controlling parameters such as output bandwidth, wavelength, energy, and dose stability of the laser, improvements can be achieved in aspects of photolithography, including overlay, CDU, and more.

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