Chapter 1
Introduction

1.1 Historical Background

For several decades, the resolution capability of optical lithography was extended by a succession of transitions to shorter imaging wavelengths. The first commercially available wafer stepper operated at a visible wavelength (436 nm), while later generations of exposure tools imaged at mid-ultraviolet and deep-ultraviolet wavelengths (Table 1.1). During efforts to continue this process of improving resolution by using a wavelength of 157 nm, with F_2 excimer lasers as the light sources, a number of difficulties were encountered, and optical lithography was eventually extended not by using light with a wavelength of 157 nm but by adapting ArF lithography to an immersion configuration that enabled the numerical aperture (NA) to be increased to 1.35. There were some additional efforts to increase the numerical aperture of ArF immersion lithography further, but development activities were eventually suspended because progress was slow.[1] The shortest wavelength used in optical lithography continues to be 193 nm.

In spite of the lack of success in developing HVM-capable lithographic technologies at 157 nm (or shorter optical wavelengths), lithographers were not ready to discontinue the pursuit of extending lithographic capability. Considerable amounts of money and engineering effort were invested in developing x-ray lithography, with a very short wavelength of ~1 nm.

Table 1.1 The wavelengths used for lithography.

Wavelength	Light source	Year of first use in high-volume manufacturing (HVM)
436 nm	Mercury arc lamp (g-line)	1982
365 nm	Mercury arc lamp (i-line)	1990
248 nm	KrF excimer laser	1994
193 nm	ArF excimer laser	2001
13.5 nm	Laser-produced plasma	2019

Unfortunately, projection optics at this wavelength could not be fabricated, principally because there are no materials that are sufficiently transparent at $\lambda \approx 1$ nm to form refractive optics, or have sufficient reflectivity for near-normal incident light, thus precluding reflective optics. This meant that x-ray lithography involved proximity printing, resulting in two significant problems. First, the patterns on wafers are replicated 1:1 from the mask, so mask quality, in terms of registration, dimensional control and defects, had to be exceedingly good. Second, fundamentally and ultimately more consequential, were the diffraction effects that became insurmountable for printing features with dimensions <100 nm.

These problems with extending optical lithography to wavelengths shorter than 193 nm involved the lack of suitable transmissive or reflective optical materials for lenses, masks, and pellicles for enabling projection lithography with reduction lenses. However, in the 1980s, multilayer films were developed that provided practical reflectivities at wavelengths $4 \text{ nm} < \lambda < 25 \text{ nm}$.[2,3] This development led to proposals for lenses with all-reflecting optics that could be used for projection lithography.[4,5,6] Initially, this was referred to as soft x-ray lithography, but the name “extreme ultraviolet” was later adopted to distinguish this new type of projection lithography from proximity 1× x-ray lithography. A nice review of the early history of EUV lithography was written by two pioneers of this technology, Dr. Obert Wood and Dr. Hiroo Kinoshita.[7] Another set of key early activities involved a consortium, the EUV Limited Liability Corporation (LLC), which produced the first full-field EUV exposure system.[8]

The consortium Sematech played a critical role in the next phase of EUV lithography development. In addition to co-sponsoring annual EUV lithography symposia, Sematech engaged in development activities directly. A small pilot line was established to produce low-defect EUV mask blanks.[9,10,11,12] The associated metrology capabilities were used to support mask blank fabrication at commercial suppliers. Sematech also funded an EUV Micro-Exposure Tool (MET) that was placed at a synchrotron light source at Lawrence Berkeley National Laboratory.[13,14] The EUV MET provided essential capability for improving EUV resists.[15,16]

Another key event in the development of EUV lithography was the decision by ASML to build a pair of full-field exposure tools, the Alpha Demo Tools (ADTs). These were installed at the consortia INVENT in Albany, NY and Imec in Leuven, Belgium, further expanding access to EUV exposure capability. The full-field exposure capability enabled the accomplishment of an important milestone in moving EUV lithography from the laboratory to the factory: the fabrication of functioning SRAMs on a test chip from Advanced Micro Devices with an interconnect layer patterned with EUV lithography.[17]

Chapter 2
Sources of EUV Light

In Chapter 1, it was explained that the wavelength of light at which EUV lithography is practiced was chosen largely by the availability of multilayers with high reflectance. This can be contrasted with the situation in optical lithography, which has always been operated at wavelengths where there are strong sources of light with narrow bandwidths. The result is that EUV lithography has suffered from light sources that are relatively weak, and a great deal of R&D has therefore gone into the development of EUV light sources in order to improve the situation.

Several methods have been used to generate EUV light. Early researchers used synchrotron light sources, but smaller light sources became needed as a practical matter as EUV lithography moved from research to development. This was true for metrology applications as well as for exposure tools, and stand-alone systems provided greater flexibility for development pilot lines. Moreover, it was eventually determined that synchrotrons of a practical size could not provide sufficient EUV light to be cost-effective, even with the use of undulators or wigglers.[1] The EUV source used currently in manufacturing tools, the laser-produced plasma (LPP) source, is discussed in this chapter, and a source that might be used in the future for wafer exposures, the free-electron laser (FEL), will also be described. Plasma-based sources used in a number of EUV metrology tools will also be described.

2.1 Laser-Produced Plasma Light Sources

The concept behind using plasmas to generate EUV light is that energetic photons can be emitted when electrons combine with highly (positively) ionized atoms. In laser-produced plasma light sources, ions are created by the strong electric fields of intense pulses of coherent laser light. These rapidly oscillating electric fields cause repeated collisions between electrons and ions, creating ions stripped of multiple electrons (see Problem 2.1). Energetic photons are produced when electrons recombine with these highly charged ions. Although atomic emissions typically occur at quantized wavelengths, for plasma-produced light, the emissions can occur over a range of wavelengths because the kinetic energy of the recombining electrons and ions also contributes to the energy of the emitted photons. The net result is emissions over a broad range of wavelengths. This is fortunate because an exact match between high multilayer reflectivity and a sharp emission line would be difficult. On the other hand, this also means that much of the light produced is not useable for wafer exposures, limiting the efficiency of plasma sources. Moreover, plasmas will produce long-wavelength DUV light that can expose resist if transmitted to the wafer plane.

The target material, often referred to as the fuel, is chosen by considering several factors. Conversion efficiency from laser light to in-band EUV light is one of the most important considerations. Xenon, tin, and lithium plasmas were found to have strong emissions in the EUV portion of the electromagnetic spectrum. A xenon jet was used in the source of the first full-field EUV exposure tool, the Engineering Test Stand (ETS), that was produced by the EUV LLC. Xenon was thought also to have an advantage in terms of optics contamination, because xenon is a noble gas. Protecting optics from chemical contamination is needed because there are no glass windows that can be used to separate the source and optics. In practice, considerable erosion of collector mirrors was observed in light sources with Xe as a fuel, even though a noble gas was used. Experiments revealed that the erosion was caused by sputtering by Xe ions with high kinetic energy.[2]

Because the mirrors needed protection from even chemically inert materials, measures were developed to reduce significantly the amount of material from the plasma (often referred to as “debris”) that reaches the condenser mirror. Consequently, non-inert materials could be considered as fuel. This led to increased consideration of tin as a fuel, because it has stronger EUV emissions than xenon, and EUV light is produced by multiple charge states of tin ions, while appreciable emission near $\lambda = 13.5$ nm is produced by only a single Xe ion (see Figs. 2.1 and 2.2). Eventually, tin became the material used in all sources for ASML’s 0.33-NA exposure tools, although Xe continues to be used for some EUV light sources, particularly for metrology (see Section 2.2).

The Engineering Test Stand (ETS) that was produced by the EUV LLC featured an LPP light source that used a pulsed Nd:YAG laser (1064-nm wavelength) to generate the plasma. There were significant doubts regarding the possibility of scaling up the power using this type of laser, and the operating and maintenance costs were high. This led to questioning LPP sources in general and resulted in substantial efforts to develop discharge-produced plasma (DPP) EUV light sources. However, these systems were unable to meet light output and reliability targets for exposure systems, so LPP sources were reconsidered. An example of a DPP source will be discussed in the next section.

Chapter 3

EUV Exposure Systems

EUV lithography exposure systems are conceptually similar to optical ones, involving light sources (discussed in the previous chapter), illumination and projection optics, alignment and focus systems, wafer stages, and sub-systems to mechanically handle wafers and reticles. Most of these need to be designed to meet the specific requirements for operation at EUV wavelengths, and the focus of this chapter is on those aspects specific to EUV lithography.

Currently, only one exposure tool supplier, ASM Lithography (ASML), is producing EUV exposure systems for use in high-volume manufacturing (HVM), and all of the projection optics are provided by Carl Zeiss. Consequently, many of the details presented in this chapter regarding EUV exposure systems are the result of specific choices made by ASML or Zeiss, while at other times, system characteristics are compelled by the physics of EUV lithography, independent of supplier. Throughout the chapter, it will be noted what is required generally and what is used specifically in the systems built by ASML. For example, the systems currently available from ASML have $NA = 0.33$, while systems with $NA = 0.55$ are under development. For both current and future systems, there was latitude for choosing the NA, but actual exposure tools have specific numerical apertures due to the choices made by the equipment and optics suppliers.

3.1 Lithography in Vacuum

An important and essential characteristic of EUV lithography systems is that exposures take place with wafers, lenses and masks under vacuum. EUV light is strongly absorbed by air, so there must be vacuum, or very low pressures, wherever actinic light is going to transit in EUV exposure tools. (The transmission of 13.5-nm light through 1 mm of air at atmospheric pressure is only ~0.1%.) There are a number of ramifications of vacuum. In optical exposure tools, air and gases perform a number of tasks, including thermal, chemical contamination, and defect control, and different approaches are required for addressing these issues in EUV exposure systems.

Temperature control is essential for stable exposure tool operation. In optical exposure tools, much attention has been paid to lens, wafer, and mask heating, since lens heating can lead to aberration errors, particularly defocus, as well as overlay errors, and the heating of wafers and masks also has an impact on overlay. Air flow is one method by which lens and wafer temperature is controlled in optical exposure tools, but the vacuum requirements in EUV systems limit the applicability of this approach. Temperature control in vacuum is more difficult than in air.

Consider, for example, a flat, solid surface over which air is flowing, with a temperature difference ΔT between the air and the solid. The rate of heat transfer per unit time q is given by[1]

$$q = h_C A \Delta T, \tag{3.1}$$

where h_C is the convective heat coefficient, and A is the area of the surface over which heat is being transferred. A useful approximation for h_C is given by

$$h_C = 10.45 - v + 10\sqrt{v}, \tag{3.2}$$

where v (m/s) is the speed of the air relative to the surface, and h_C is measured in units of W/m^{2}K. If we assume that there is a temperature difference of ΔT = 0.1 K and v = 1 m/s, then the heat transfer per unit area is given by

$$\frac{q}{A} = 1.95\mathrm{W/m^2}. \tag{3.3}$$

In EUV lithography systems, there cannot be air flows at pressures that are an appreciable fraction of atmospheric pressure. Gas flows at low pressure can be used to achieve levels of heat transfer that are sometimes useful, but the efficacy of such flows is much reduced compared to what occurs at atmospheric pressure. The remaining mechanisms of heat transfer are conduction and radiation. The rate of radiative transfer per unit area between two flat, parallel surfaces is given by[2]

$$\frac{q}{A} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}, \tag{3.4}$$

where σ is the Stefan–Boltzmann constant, and ε_1 and ε_2 are the emissivities of the two surfaces, which are at temperatures T_1 and T_2. If we assume $\varepsilon_1 = \varepsilon_2 = 1$, and that one surface is at a temperature of 300.0 K while the other has a temperature of 300.1 K, then the rate of heat transfer by radiation is approximately 0.2 W/m^2. Comparing this with Eq. (3.3), one can see that convection is a much more efficient means for controlling temperatures by approximately an order of magnitude.

Chapter 4

EUV Masks

As discussed previously, there are no high-transmission optical materials at EUV wavelengths due to limitations imposed by atomic absorption. As a consequence, all optical elements in the lens must be reflective for EUV lithography.[1] Similarly, EUV masks must be either reflective or stencil-type. The semiconductor industry has made reflective masks standard, as they were seen as more practical than stencil masks. This means that masks for EUV lithography are fundamentally different from those used for optical lithography. An extensive amount of engineering effort was directed at determining what the format should be for reflective EUV masks, and additional effort was required to make them suitable for use in high-volume manufacturing.

4.1 Structure of EUV Masks

A typical configuration for an EUV mask blank is shown in Fig. 4.1. A multilayer reflector is deposited on the front side of a flat, glass substrate. A capping layer, typically ruthenium, is deposited on the multilayer, and then the absorber is deposited on the capping layer. Because the absorber is typically metallic, optical contrast is low between the absorber and multilayer, making defect inspection difficult. Consequently, a thin film is often deposited on top of the absorber to increase the contrast at DUV wavelengths. An electrically conductive backside film is also deposited to enable the mask to be secured on electrostatic chucks in exposure tools. Electron micrographs of an early EUV reflection mask are shown in Fig. 4.2.

As in optical binary masks, EUV binary masks are divided into "dark" and "light" areas, but for EUV lithography, the light areas are reflective rather than transmissive, while the dark areas are covered by absorbers to prevent reflection. For early EUV masks, gold was often used as an absorber, as also used for many 1× x-ray masks, even though lift-off processes were required for fabrication, due to the absence of a process for dry etching gold. Potential absorber materials that could be dry-etched were considered, such as chromium, which was a standard absorber material for optical masks, and TiN.

Chapter 5

EUV Resists

To date, most resists used for EUV lithography are chemically amplified resists, based on KrF and ArF resist platforms (although new concepts are also being given serious consideration). However, the demands for EUV resists differ from those of photoresists used at optical wavelengths in some critical ways. Because EUV lithography is intended to be used to produce features and pitches beyond the resolution limits of ArF lithography, EUV resists must be capable of very high resolution and have low line-edge roughness. There is also an enhanced need for sensitivity because of the low output of EUV light sources compared to excimer lasers, a problem described in Chapter 2. For DUV resists, sensitivity has been obtained through chemical amplification, and the greater the extent to which photoacids can diffuse and produce deprotection, the fewer photons are required to expose the resist. However, substantial diffusion will effectively blur the image, reducing resolution. To maintain a high-resolution image after post-exposure bake, there is a rule of thumb that the diffusion length of the photoacids in chemically amplified resists should be less than ~16% of the pitch.[1] Using this estimate as a guide, for 20-nm half-pitch technology, the diffusion length will need to be less than ~6 nm and must be even smaller for later nodes. In addition to having much tighter requirements for resolution and LER, the mechanisms of the radiation chemistry of EUV resists are different from those of optical resists, and these mechanisms for EUV resists are discussed in the first section of this chapter.

5.1 Exposure Mechanisms of Chemically Amplified EUV Resists

In KrF and ArF chemically amplified resists, incident photons are absorbed by photoacid generators, with acids produced as a direct consequence of this photoabsorption.[2] The radiation chemistry in EUV resists involves a somewhat different mechanism. EUV photons are highly energetic (~92 eV), so photoabsorption typically results in the generation of a photoelectron. Acids are produced as the result of collisions between electrons and

Chapter 6
Computational Lithography for EUV

Early work on EUV lithography primarily involved patterning at large values of k_1, at least in comparison to what had been routine for optical lithography for many years. For example, EUV lithography was introduced into high-volume manufacturing at the 7-nm node, with ~20-nm half-pitch, giving $k_1 = 0.49$, while k_1 has been considerably less than 0.4 for logic using optical lithography since the 32-nm node. Although there were some early studies indicating that an accurate description of imaging for EUV lithography was necessarily complex, most of the complications were seen to occur at low values of k_1, so the computational aspects of EUV lithography required to address many issues received much less attention than other aspects of the technology for a number of years. However, in order to meet the requirements of the 5-nm node and beyond, many computational aspects of EUV lithography need to be considered, and there has been much recent work.

There are several reasons why computational lithography for advanced EUV lithography is more complex than it is for optical lithography. To begin, OPC for EUV lithography still has all of the requirements of conventional, optical OPC, such as the need to ensure good targeting of dimensions at the best operating point and good dimensional control throughput the process window, which includes variations on the mask. Because EUV lithography is applied at the most advanced nodes, accuracy requirements are necessarily tighter than they are for optical lithography. There are some differences between the conventional OPC for EUV lithography and that for optical lithography. For example, it is important for both lithographic technologies to ensure that the image log-slope maintains a certain minimum, but this metric may get greater emphasis in EUV lithography. As noted in Chapter 5, the impact of resist stochastics can be reduced by maintaining a large normalized image slope, so more weight may be given to this image metric during OPC optimization.

Chapter 7

Process Control for EUV Lithography

There are several sources of process variation that are unique to EUV lithography or of significantly greater significance than in optical lithography. The issues for overlay, linewidth control, and defects relevant to EUV lithography are discussed in this chapter. Recently, attention has been given to the subject of edge placement errors, which result from a combination of critical dimension and overlay errors.[1] Although edge placement is the fundamental quantity of interest, overlay and critical dimension control will be considered separately in this chapter so that the causes of process variations can be understood more clearly. Metrology is an important consideration for process control and is the topic of the next chapter.

The application of EUV lithography only to very advanced nodes (7 nm and beyond) means that process control requirements are always very tight. Selected dimensions and control requirements from the 2020 International Roadmap for Devices and Systems (IRDS) are shown in Table 7.1. As can be seen, control is expected to be required at the nanometer and sub-nanometer

Table 7.1 Values for selected critical dimensions and control requirements for logic from the 2020 International Roadmap for Devices and Systems (IRDS).

Logic industry "Node" labeling (nm)	"7"	"5"	"3"	"2.1"	"1.5"	"1.0"
Year of production	2018	2022	2022	2025	2028	2031
MPU/ASIC minimum metal half-pitch (nm)	18.0	15.0	12.0	10.5	8.0	8.0
Metal LWR	2.7	2.3	1.8	1.5	1.2	1.2
Metal CD control (3σ) (nm)	2.7	2.3	1.8	1.5	1.2	1.2
Gate LER	0.8	0.7	0.6	0.5	0.5	0.5
Physical gate length for HP Logic (nm)	20	18	16	14	12	12
Gate CD control (3σ) (nm)	1.1	1.0	0.9	0.7	0.6	0.6
Overlay (mean + 3σ)	3.6	3.0	2.4	2.1	1.6	1.6

level, that is, at the molecular scale (see Chapter 5). Meeting these requirements is challenging, particularly because there are mechanisms that induce process variations for which there are no counterparts in optical lithography, as will be seen in this chapter. Improvements of just a few tenths of a nanometer are significant for advanced nodes. For example, reducing the overlay by only 0.5 nm at the 5-nm node is a 17% improvement relative to the target.

7.1 Overlay

For overlay, all of the issues that are relevant for optical lithography pertain to EUV lithography. These include matters such as alignment and overlay measurement mark quality, overlay modeling, and mask and wafer heating. Some contributions to overlay errors, such as aberrations, are relevant for optical lithography but are more significant for EUV lithography. There are also some additional contributions to overlay errors for EUV lithography for which there are no counterparts in optical lithography, and these will be discussed in this section.

As noted in Chapter 4, mask nonflatness causes overlay errors in EUV lithography. For optical photomasks, an overall flatness of 100 nm is a typical requirement for leading-edge masks, driven by focus control considerations, with tighter flatness adding to blank costs. For EUV masks, much tighter flatness is required because of the impact on overlay. For example, only 50-nm nonflatness will lead to 1.3-nm overlay error at the wafer level (see Problem 4.3). This is a substantial fraction of the total overlay budget at the 7-nm node and beyond (Table 7.1). Without some method of compensation, for mask nonflatness to contribute an overlay error that is only 10% of the total overlay budget for the 5-nm node, mask flatness would need to be <10 nm. This would lead to extremely expensive masks, particularly since the additional polishing needed to attain such flatness would increase defects.

There are also overlay errors that can result from mask backside nonflatness, even if the frontside of a chucked EUV mask is flat (see Fig. 7.1). When the mask is chucked, there will be in-plane distortion that is proportional to the backside slope ϕ:[2,3]

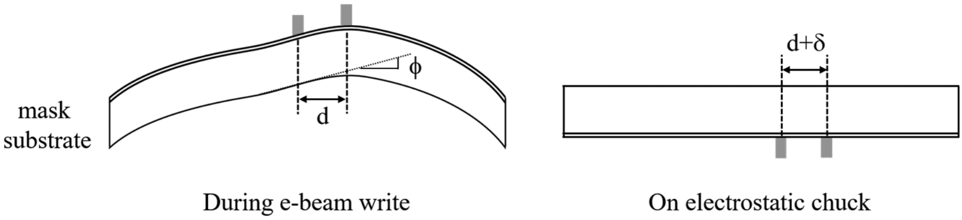

Figure 7.1 Mask shape during e-beam write and when on the electrostatic chuck.

Chapter 8

Metrology for EUV Lithography

Much of the metrology for EUV lithography is similar to that for optical lithography, with the caveat that EUV lithography is practiced at very small dimensions. Measurements of overlay and critical dimensions are needed, but since they have the same issues as they did for optical lithography, they will not be discussed in detail in this book. On the other hand, there are aspects of EUV technology without counterparts in optical lithography, mostly related to masks and pellicles, and these have special metrology requirements. Importantly, many metrology tools involve measurement at EUV wavelengths, which necessitates the use of specialized light sources and operation in vacuum.

Measurement tools are needed for the development and manufacturing of certain components, such as EUV mask blanks. These are of interest to practicing lithographers, even though such tools are not necessarily used in wafer fabs or masks shops, since it is often important for lithographers to understand the quality control capabilities of their suppliers. One of the earliest tools to be built in support of EUV technology development was a reflectometer at EUV wavelengths.[1] Such tools are used to measure multilayer reflectivity and uniformity on EUV mask blanks. Typically arranged to provide measurements of reflectivity at a 6° angle of incidence, the same as the chief ray angle of 0.33-NA exposure tools, these reflectometers can measure absolute reflectance over a range of wavelengths about 13.5 nm. These data can be used to determine the wavelength of peak reflectivity and the reflectance uniformity across mask blanks. Prior to the introduction of such standalone tools in 2002, measurements of reflectivity at EUV wavelengths were typically performed at electron storage rings. Standalone tools are much more convenient for manufacturers of EUV mask blanks. They can also be used to measure the impact of processing on multilayer reflectivity and changes in reflectivity over time. Standalone tools are currently available from EUV Technology, Inc.[2] and Research Instruments GmbH.[3] Laboratories using synchrotron light sources continue to provide important calibration (as well as other) services.[4,5,6]

Chapter 9

EUV Lithography Costs

Because the equipment and materials for semiconductor lithography are expensive, the overall cost of lithography has received considerable attention. There are a number of components that contribute to lithography costs (Table 9.1), and each of these will be discussed in more detail in this chapter as they pertain to EUV lithography. Because the impact of mask costs is highly dependent on the number of wafers produced per mask, wafer and mask costs are considered separately, although the situation for EUV lithography is somewhat more complex than for optical lithography, at least for situations in which pellicles are not in use.

Table 9.1 Categories for EUV lithography costs.

Wafer costs	Capital costs: tool prices, throughput, availability
	Maintenance costs
	Metrology, including mask qualification
	Operating costs: consumables, utilities
Mask costs	Blank costs
	Capital costs

9.1 Wafer Costs

9.1.1 Capital costs

EUV exposure tools cost in excess of \$120M.[1,2] In order to realize a positive return on investments in such equipment, a high level of productivity per tool is necessary. The basic capital cost per wafer exposed is

$$\text{cost/wafer} = \frac{C_{ED}}{T_p U}, \tag{9.1}$$

where C_{ED} is the capital depreciation per hour, T_p is the raw throughput of the system (in wafers per hour), and U is the fractional equipment utilization.

Chapter 10

Extending EUV Lithography

Lithographic technology has been extended for several decades through a combination of reduced k_1, increased numerical aperture, shorter wavelengths, and the use of multiple patterning. All of these are possible for EUV lithography and are the topics of this chapter. Because this chapter addresses future technologies that are still undergoing development, much of the text consists of descriptions of known problems that engineers need to solve, rather than explanations of solutions.

10.1 How Low k_1 Can Go

In the 1980s, it was conventional wisdom that k_1 needed to be 0.8 or larger in order to have a manufacturable process. Over time, improvements were made in resists, optics, and process control, and wavefront engineering was introduced, leading to useable values of k_1 for optical lithography below 0.3 and close to the physical limit of 0.25. For the full potential of EUV lithography to be realized, such low values of k_1 also need to be reached. EUV lithography has first been applied in high volume manufacturing to technologies with pitches ~40 nm, which represents a k_1 of 0.49, indicating that opportunities exist for the further reduction of k_1, although there are challenges.

The fabrication of lenses with extraordinarily low aberrations was a significant reason that k_1 could be lowered for optical lithography. Aberrations on EUV exposure tools are below 0.2 nm rms.[1] Although impressive on an absolute scale, this level of aberrations is ~15 mλ, which is much higher than the levels achieved in optical exposure tools (<4 mλ).[2] As a consequence, it will be difficult with EUV lithography to achieve the same low levels of k_1 reached with optical lithography. Nevertheless, with the level of aberrations existing in EUV lenses, substantial reductions below $k_1 = 0.49$ can still be expected. Further decreases in aberrations in EUV optics can also be expected, even if the same level of aberrations found in state-of-the-art immersion lenses is not achieved. Exactly how small a value of k_1 can be achieved will depend on how successfully the problems discussed in this chapter are solved.