Extreme Ultraviolet Lithography

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(Invited Paper)

***Abstract*—Current microlithography used in high-volume integrated circuit manufacturing employs some form of optical projection technology. The most advanced tools use deep-ultraviolet (DUV) radiation having a wavelength of 248 nm and are used to print 250-nm features. These tools will likely be extended for use at the 180-nm generation and perhaps below. New DUV tools using 193-nm radiation are actively under development and are expected to be used for 130-nm generation and perhaps even 100-nm generation. Extending these DUV optical projection tools for manufacturing in the 100–200-nm region will be paced by the development of new high numerical aperture imaging systems and highly complex phase shift masks. For future generations of integrated circuits with minimum feature sizes below 100 nm, 193-nm tools will have great difficulty meeting all manufacturing requirements. This paper describes an alternate optical approach, for sub-100-nm generations, based on extreme ultraviolet radiation at around 13 nm, called extreme ultraviolet lithography (EUVL). This approach uses a laser-produced plasma source of radiation, a reflective mask, and a 4× reduction all-reflective imaging system. The technology is currently in the engineering development phase for an alpha machine. This paper reviews its current status and describes the basic modules or building blocks of a generic EUVL exposure tool.**

***Index Terms*— Lithography, semiconductor device manufacture.**

I. Introduction

LITHOGRAPHY development is generally viewed as the gating technology for each new generation of semiconductor devices. For the last several decades, optical projection lithography has been the lithographic technology of choice for high-volume manufacturing of integrated circuits, and it is now widely accepted that improvements in optics and mask technologies will allow it to extend toward the 100-nm minimum feature size region. Extension of optical lithography has been made possible by continuous reduction in the exposure wavelength and simultaneous increases in numerical aperture (NA). Both trends provide increases in resolution at the cost of smaller depth of focus. The question of how long this trend can continue, and how far down in feature size optical lithography using refractive transmission lens designs can go, is one that continues to be actively debated. The National Technology Roadmap for Semiconductors (NTRS) [1] shows optical lithography as the desired mainstream approach down to at least 130 nm. At these feature sizes, all of the optical approaches require extremely complex phase shift masks and off-axis mask illumination. Both serve to drive manufacturing costs up, fueling the controversy as to how long these optical lithography extensions can continue to be a cost-effective solution.

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TABLE I
Lithography Technologies for the 250-nm Generation and Below

	Lithography Solution (wavelength)
250 nm	Optical (248 nm)
180 nm	Optical (148 nm, 193 nm)
130 nm	Optical (193 nm, 248 nm)
100 nm	Optical (193 nm), e-beam, EUV (13 nm)
70 nm	EUV (13 nm), e-beam
50 nm	EUV (13 nm), e-beam

Below 100 nm, new approaches are needed. At least four approaches, called the "Next-Generation Lithographies," have demonstrated feasibility and are in various stages of subsequent research and development. These are extreme ultraviolet lithography [2] (EUVL) (4× reduction with 13.4-nm radiation using reflective optics and mask), SCALPEL [3] (4× reduction e-beam and scattering membrane mask), X-ray [4] (one-to-one membrane mask with X-ray), and ion beam (4× reduction and stencil mask). Within the U.S., EUVL is being developed by the Extreme Ultraviolet Limited Liability Corporation, SCALPEL is under development by Lucent Technologies and X-ray one-to-one printing continues to be developed principally by IBM. Table I summarizes the future options.

The basic components of an optical projection lithography system include a source, a condenser (to collect the source radiation and direct it onto the mask), a mask containing the pattern to be printed on the wafer, and a reduction imaging lens assembly that projects an image of the mask onto the silicon wafer. The ability to print very fine features, or the resolution, of these systems is proportional to the exposure wavelength divided by the numerical aperture of the lens assembly. The constant of proportionality, the so-called K_1 constant, is an empirical factor dependent on resist properties, use of mask resolution enhancement technologies (e.g., optical proximity correction patterns, phase shifting features, etc.) and the illumination properties of the condenser. Fig. 1 shows the dependence of resolution on the exposure wavelength, λ and K_1 (assuming a numerical aperture of 0.7) for current I-line

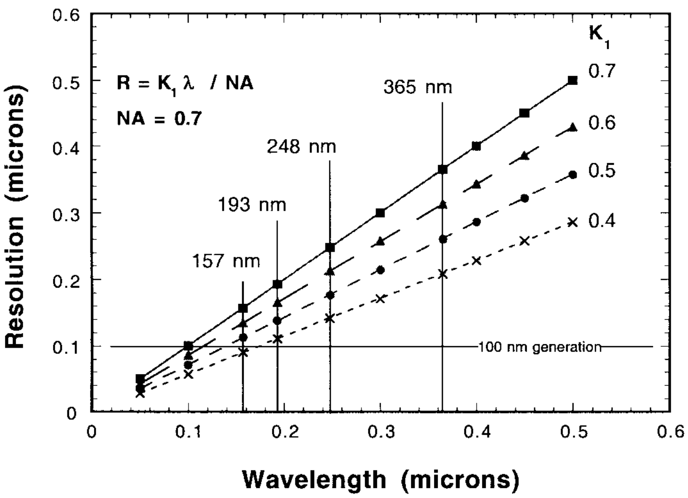


Fig. 1. Resolution as a function of wavelength for a lithographic imaging system with numerical aperture of 0.7 for various k_1-factors. K_1-factors of 0.7 are common in manufacturing. Achieving $k_1 < 0.7$ requires utilization of annular or off-axis illumination, resolution enhancement techniques, or novel resist processes.

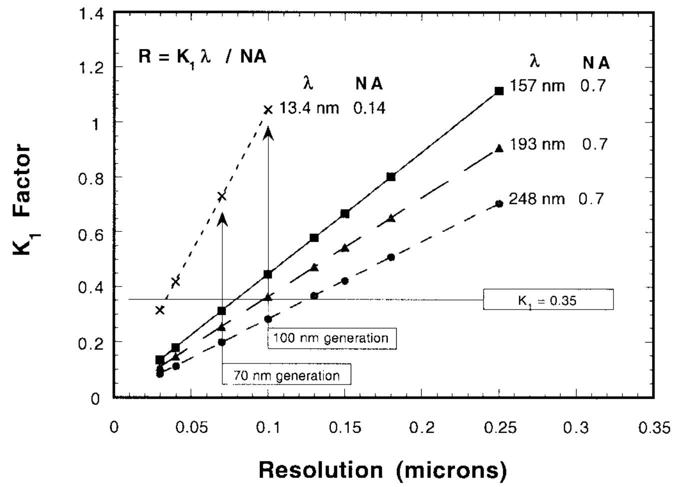


Fig. 2. K-factor required to meet resolution targets for each of the optical technologies assuming an NA $= 0.7$ for the DUV approaches and NA $= 0.14$ for EUV.

(365 nm), deep-ultraviolet (DUV) technologies (193 and 248 nm) and 157-nm lithography, currently being debated as a potential extension of 193 nm.

Development of lithography using 157-nm light (F_2 laser) would require the use of CaF_2 for lenses since the transmission properties of fused silica fall off significantly below 180 nm. However, even CaF_2 has some absorption at 157 nm which would result in heating of the lenses and mask, causing distortion due to dn/dT (where n is the index of refraction), and pattern placement errors at the wafer due to thermal expansion of the mask substrate. This becomes a serious issue at the 100-nm generation since the coefficient of thermal expansion of CaF_2 is 36 times larger than that for fused silica, used for masks in current optical steppers. This thermal problem becomes even larger for e-beam patterning of the mask blanks since more energy is deposited over a localized region during this process.

As can be seen from Fig. 1, extending optical projection lithography has become dependent upon decreasing the k_1-factor by changing from simple Gaussian or top-hat illumination to annular or quadrapole illumination, and by incorporating resolution enhancement or phase-shifting features into the mask pattern. Of these, the mask problem is substantially more complex and costly. Thus, the difficulty of extending optical lithography tools has become a k_1-factor or mask manufacturing problem.

Developing a manufacturable integrated circuit (IC) process that relies on a k_1-factor of less than 0.6 is nontrivial. Factors having nothing to do with the imaging system, such as the resist and etch process, have a major impact on determining these values. Fig. 2 shows the required k_1-factors for the various optical approaches.

Manufacturing processes below $k_1 \sim 0.6$ must use complicated resolution enhancement technologies (RET) such as phase-shifting structures and optical proximity correction. To extend to the 70-nm generation, all optical lithographies except EUV will require resolution enhancements.

II. EUV Lithography

As was presented above, the motivation for going to EUV wavelengths is driven by limitations in achieving high resolution imposed by the relationship between the operating wavelength and the NA of the imaging system. However, as the operating wavelength is reduced below 150 nm, all materials become opaque, requiring the use of reflective designs with optics using special coatings to achieve high reflectivities at the operating wavelength. To a large degree, EUVL has been made possible by the development of advanced multilayer coatings at Lawrence Livermore National Laboratory, Livermore, CA. and Lawrence Berkeley National Laboratory, Berkeley, CA, that now achieve reflectivities of 70% in the EUV [5]. Fig. 3 shows a transmission electron micrograph (TEM) of a multilayer coating made from alternating layers of Mo and Si and the associated reflectivity curves for MoSi and MoBe. Both of these coatings operate with sufficient reflectivity to be useful for EUVL applications. MoSi is optimized for use at 13.4 nm while MoBe is designed for 11.3-nm operation.

The fundamental concept for a simple EUVL imaging camera is shown in Fig. 4. EUV radiation from laser-produced plasma [6] illuminates a mask containing the pattern to be replicated on an Si wafer substrate where the IC's are built. The mask pattern is then imaged by a reduction imaging system and brought into focus at the wafer.

The basic building blocks of a commercial EUVL tool are similar to what is found in optical steppers except that their form is different due to the short wavelength of EUV. Since all materials, including nitrogen and oxygen, absorb strongly in this spectral region, the machine must operate in a vacuum using reflective mirrors and masks. The choice of the specific operating wavelength is determined by the availability of the multilayer coatings as first discussed by Kinoshita *et al.* [7]. The coating selection for use in manufacturing will ultimately depend upon source brightness and wafer throughput requirements. Current imaging systems all use MoSi due to the maturity and vast amount of information known for this material combination. However, it is likely that

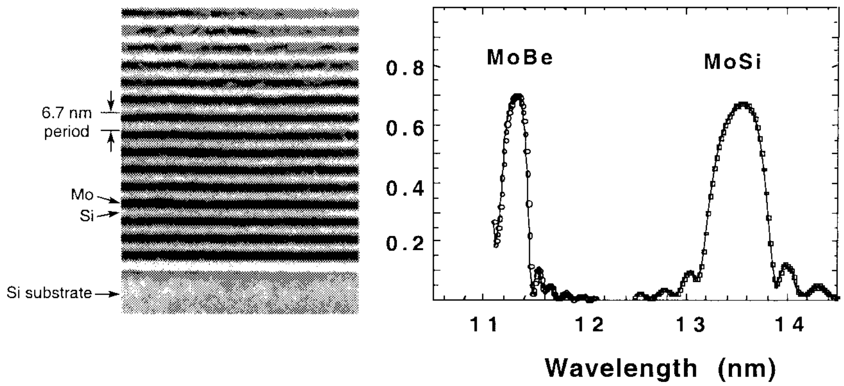


Fig. 3. TEM of a portion of a MoSi multilayer coating used at 13.4 nm is shown on the left (courtesy D. Attwood). On the right are typical reflectivity curves for MoSi and MoBe.

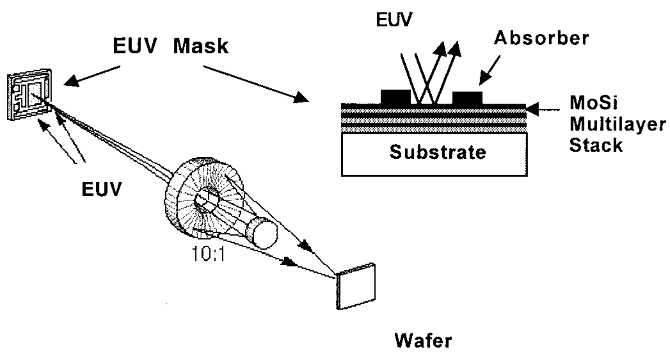


Fig. 4. Schematic of a simple EUV imaging system showing the mask, imaging optics, and wafer (courtesy of D. Attwood). Both the mask and the optics are multilayer coated. In the upper right of the figure is shown a more detailed view of the mask structure composed of a substrate, multilayer coating, and absorber to define the pattern to be printed.

other multilayers will be used that are either better matched to source spectra or have intrinsically higher reflectivity and would thus lead to reduced exposure times and higher wafer throughput.

III. Laboratory EUV Microstepper Development

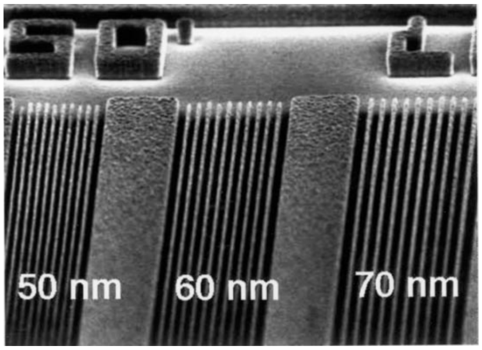
The first successful demonstrations of EUV reduction imaging were published by Kinoshita *et al.* in 1989 and shortly thereafter by Bjorkholm *et al.* [8] in 1990. Both groups utilized two-mirror Schwarzschild imaging systems similar to that shown in Fig. 4 and EUV generated from synchrotron radiation sources. In 1991, Sandia National Laboratories and AT&T Bell Laboratories duplicated these results using a compact laser plasma source [9], paving the way for increased industrial interest. The first 20× reduction Sandia camera was later upgraded to a 10× reduction system with a larger field of view, approximately 0.5 mm in diameter. While extremely small, this field size is more than adequate for process and component development. The 10× reduction camera was subsequently integrated into a complete microstepper [10] with overlay capability used to fabricate MOS devices [11].

In the current 10× microstepper, EUV is generated by a laser-produced plasma source (LPS) created by focusing, 1064-nm radiation from a commercial Nd : YAG laser (40 W at 100-Hz operation, ~5-ns pulse duration) onto Xe clusters produced by a pulsed gas jet system. An elliptical condenser collects 2.5% of the available 2π sr EUV radiation and projects it onto the mask in the camera chamber. The mask subsequently reflects the EUV into a subaperture of a two-element Schwarzschild camera, which images the mask pattern with a 10× reduction ratio onto a resist-coated wafer. The wafer is held by an electrostatic chuck mounted on a magnetically levitated wafer stage that is controlled by a grazing-incidence focus system and conventional laser interferometry.

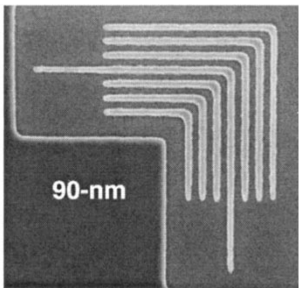
Fig. 5 shows representative images in high-resolution resist. Due to the large absorption coefficient, only thin layer imaging is possible. Sub-90 nm resolution has been demonstrated using both top surface imaging (TSI) and ultra-thin resist (UTR) approaches. One of the attractive features of EUV is the exposure linearity that can be achieved with low NA imaging systems. The measured linewidth for features from 200 to 80 nm produced on the 10× system is shown in Fig. 6 as a function of the predicted feature size as coded on the mask for a single-exposure dose. The results demonstrate the expectation of near perfect linearity whereby, after development, all features exposed at the same dose exhibit the predicted feature size. For large NA systems typical of DUV tools, linearity may not be preserved for critical dimensions near the exposure wavelength. To compensate, features of different sizes on the mask are biased differently so that, after exposure and development, they come out at the proper dimension.

IV. Alpha Machine Development

Hawryluk and Seppala [12] described an early concept of an imaging system using EUV radiation in 1988. Later, Jewell published designs for four-mirror ring-field imaging systems [13]. Improved designs have recently been reported, and Fig. 7 shows an example of a modern design [14] of an EUVL camera containing four mirrors. Specifications for the figure and finish for EUV camera mirrors scale with the wavelength and are given in the table shown in this figure. The figure requirement depends on the number of mirrors in the imaging system and is determined by requiring that, when summed together, the errors from the individual mirrors add in such a way that the total wavefront error of the assembled camera cannot exceed approximately 0.07 waves. The midspatial frequency roughness requirement is



(a)



(b)

Fig. 5. Patterns printed in 800 nm of resist using a 10× reduction EUV laboratory tool. (a) The electron micrograph shows a variety of features with critical dimensions down to 50 nm, while the features in (b) show excellent isolated and dense 90-nm features.

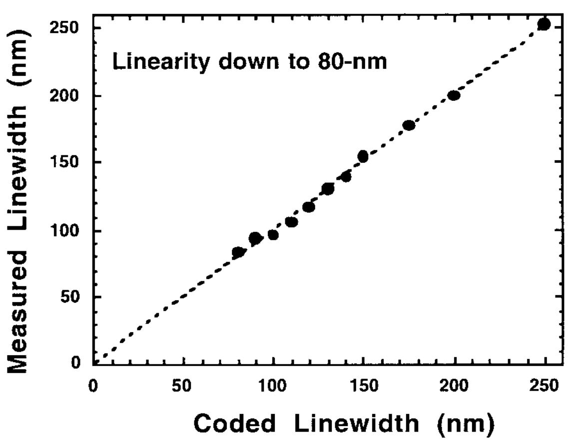


Fig. 6. Plot showing the linear relationship between the measured feature size on a printed wafer versus the predicted, or coded, feature size on the mask. These results were achieved without mask biasing or other resolution enhancement features.

a function of the allowed flare in the camera and the its relationship to critical dimension control over the printed field. Finally, the high-spatial frequency roughness, defined as that above frequencies of 1 μm^{-1}, is set by the requirements on multilayer reflectivity. Current fabrication results on aspheric optics have achieved 0.4-nm figure, 0.15-nm mid-spatial frequency roughness, and 0.1-nm high-spatial frequency roughness.

An alpha-class EUV tool is now under development at Sandia National Laboratories, Lawrence Livermore Laboratory, and Lawrence Berkeley Laboratory, based upon the

Figure	0.25 nm rms
Mid-spatial frequency	0.20 nm rms
High-spatial frequency	0.10 nm rms

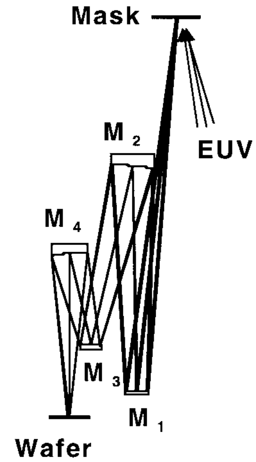


Fig. 7. At the right of this figure is shown a four-mirror EUVL imaging system comprised of a reflective mask, a set of projection optics, and a resist-coated wafer. At top left are fabrication specifications for the projection optics substrates.

optical design shown in Fig. 8. This tool (Fig. 8), called the engineering test stand (ETS) has six essential subsystems: a laser-produced plasma EUV source, condenser optics, projection optics, mask, precision scanning stages, and a vacuum enclosure. There are nine optical reflections in the ETS, seven of which are from near normal incidence multilayer-coated substrates. Focus, alignment, and scanning stage approaches are expected to be identical to what is in use today and do not require any EUV-specific development. While EUV has the same types of subsystems found in current step-and-scan DUV tools, the embodiment of these subsystems is different. The most significant differences are found in the source, the reflective optics and mask, and the need to operate in a moderate vacuum.

V. EUV Optics

Successful implementation of EUVL presents a number of technical challenges, especially in the fabrication and testing of optics substrates. High-accuracy metrology tools are prerequisites for fabricating these precision optics. Improvements in figure metrology have been made that enable the absolute measurement of surfaces to the accuracy required. The first of these innovations is the phase-shifting diffraction interferometer (PSDI) [15], which has demonstrated surface figure measurement accuracies of <0.25-nm rms. This interferometer utilizes visible light and is in use in optical fabrication facilities for the fabrication of the EUV mirror substrates. Since the optical system must be characterized after the optics are coated with multilayer reflectors, measurement of the final assembled optical system wavefront error will be performed using light at the wavelength of intended operation. An EUV interferometer has been developed that is used to characterize the final wavefront quality of the entire camera and make final adjustments as needed. A significant recent accomplishment is depicted in Fig. 9. The figure shows side by side comparisons of visible light and EUV-wavelength interferometry inspecting the same 10× microstepper optical system. Although the measurements were made by different research groups (LBNL and LLNL)

Specification	Beta
Numerical Aperture	0.14
Demagnification Factor	4
Operating wavelength	11.2 nm
Resolution (assuming K_1 = 0.5)	40 nm
Average Laser Power	1500 W
EUV flux to wafer	155 mw/cm^2
Wafer Throughput (300mm wafers)	40 wph

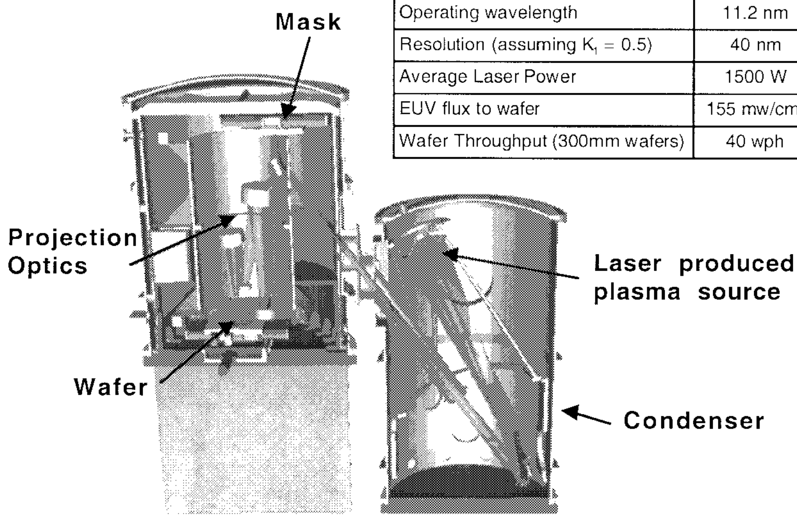


Fig. 8. Concept model of an Alpha-class tool called the ETS design to accelerated development of commercial EUVL tools. In the upper portion of the figure are a set of high-level specifications for beta tools that are capable of achieving wafer throughputs of 40 300-mm-diameter wafers per hour.

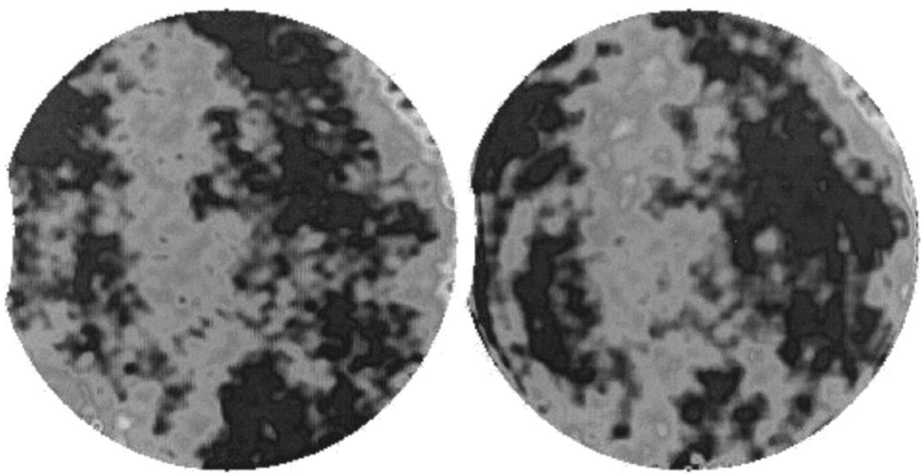


Fig. 9. Side by side comparison of interferograms of an assembled 10× EUV camera. The one on the left was taken with EUV light while the one on the right was taken with visible light. The rms values differ by only approximately 0.02 nm. The rms wavefront error for each is approximately 0.8 nm. (Courtesy D. Attwood).

with fundamentally different interferometric techniques and with wavelengths differing by a factor of forty, the two techniques agree to within 0.02 nm rms.

To preserve the figure of the EUVL projection optics, the multilayer coatings must be controlled in thickness to about 0.1% rms. This imposes rigorous control on the uniformity of the multilayer period thickness over the surface of the substrate. The LLNL multilayer group has recently reported results of coating MoSi multilayers with a uniformity of better than 0.01% over an 80-mm-diameter region.

VI. Summary

DUV optical projection lithography continues to be used in volume IC manufacturing and, while significant uncertainty and risk exists, is now projected to be extended down to nearly the 100-nm generation. Achieving these critical dimensions will come at the expense of increasing risks associated with more complex DUV imaging cameras and costly mask technologies. EUVL represents the ultimate extension of DUV and achieves high resolution and depth of focus by reducing the operating or exposure wavelength by a factor of roughly 20, from 248 nm down to 13 nm. This brings the advantages of low NA optical imaging systems but requires the introduction of reflective optics and mask technologies. Considerable progress has been achieved in EUV over the past several years, especially in the component technologies such as optics and metrology, and in integrated tool development. With continued research and development, the remaining necessary improvements in masks, resists, and machine engineering can be achieved, positioning EUVL for volume manufacturing midway through the next decade.

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Results of his research have been extensively published through over 100 journal and meeting papers. He is currently the project leader for EUVL at Lawrence Livermore National Laboratory, Livermore, CA.