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Extreme ultraviolet lithography: Status and prospects

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Extreme ultraviolet lithography (EUVL) using 13.5 nm wavelength light is the leading candidate to succeed 193 nm immersion lithography, enabling semiconductor chips with features smaller than 22 nm. Several major programs worldwide have developed this technology in recent years [D. A. Tichenor *et al.*, OSA Proceedings on Soft X-Ray Projection Lithography, edited by A. M. Hawryluk and R. H. Stuten (1993), Vol. 18, p. 79; H. Kinachita, OSA Proceedings on Soft X-Ray Projection Lithography, edited by A. M. Hawryluk and R. H Stulen (1993), Vol. 18, p. 74; J. P. H. Benschop, W. M. Kaiser, and D. C. Ockwell, Proc. SPIE **3676**, 246 (1999)] and in 2006, ASML shipped the first EUV Alpha Demo tools (NA=0.25 full-field scanners) to IMEC in Belgium [A. M. Goethals *et al.*, Proc. SPIE **6517**, 651709 (2007)] and CNSE in Albany [O. Wood *et al.*, Proc. SPIE **6517**, 6517–041 (2007)], USA. Currently the development of preproduction tools with targeted shipment of 2009 is well under way. This paper discusses the most critical items for EUVL development, namely, EUV imaging and EUV sources. Furthermore, it elaborates on the necessary development of masks and resists and, for example, quantifies how resist diffusion length can impact imaging capabilities. Results obtained and lessons learned with the Alpha Demo tools are discussed, as well as potential solutions to some of the remaining challenges. Additionally, this paper explains how EUV can realize high productivity (>100 wafers/h) and high resolutions (<22 nm) to continue the cost-effective shrink of semiconductors for several generations. © *2008 American Vacuum Society.* [DOI: 10.1116/1.3010737]

I. INTRODUCTION

The resolution of optical lithography scales with k_1 (an imaging enhancement dependent parameter) and the wavelength of the light used, and it is inversely proportional to the numerical aperture (NA) of the lithography system's lens. A lower k_1 generally leads to lower modulation of the light at the wafer and thus to lower process margins. Imaging enhancement technologies[1] can be applied to mitigate part of this effect; however, the physical limit of single exposure lithography is $k_1=0.25$. Table I shows how various combinations of NA, wavelength, and k_1 can be used to meet the required resolution over time.

State-of-the-art optical lithography uses water-based immersion technology, an ArF laser source with 193 nm wavelength, and an objective lens having a numerical aperture of 1.35.[2] It can be used to print lines and spaces close to the physical limit of 36 nm half-pitch. It is expected that extreme ultraviolet lithography (EUV) tools and infrastructure will not be ready in time to produce chips at the 32 nm half-pitch node, which will likely require a form of double patterning. The May 2008 Litho Forum in Bolton Landing, organized by SEMATECH, confirmed that EUV is the preferred technology from 2012 onward and will predominate in 2016.[3] According to the 2006 ITRS roadmap, a 22 nm half-pitch system would be in production in 2016.[4] EUV is likely to be introduced for 22 nm half-pitch manufacturing and extended to 11 nm half-pitch and beyond. At its introduction, the k_1 value of EUV will be 0.4 or larger, which is a significant advantage in manufacturing compared with today's 193 nm lithography operating with k_1 close to the physical limit.

II. RESULTS FROM THE ALPHA DEMO TOOLS

Two Alpha Demo tools were built[5] and shipped by ASML in 2006, one to IMEC (Interuniversitair Micro-Electronica. Centrum) in Belgium and one to CNSE (College of Nanoscale Science and Engineering) in the USA. These are full-field (26×33 mm^2) EUV scanners, primarily intended to build knowledge on tool technology, and mask- and-resist infrastructure. At the time of shipment, only low-power sources were available. Nevertheless the tools exposed about 250 full field 300 mm wafers between October 2007 and February 2008. Sixteen different reticles from three reticle blank suppliers and different resists were used.

TABLE I. k_1 value as function of resolution (defined as half-pitch), wavelength λ, and numerical aperture NA. Values below 0.25 require double patterning.

Half-pitch (nm) year		65	45	32	22	16	11
λ (nm)	NA	2005	2007	2009	2011	2013	2015
	0.93	0.31					
	1.20	0.40	0.28				
193	1.35		0.31	0.22	0.15		
	1.55			0.26	0.18		
13.5	0.25			0.59	0.41		
	0.35				0.57	0.41	
	0.45					0.53	0.37

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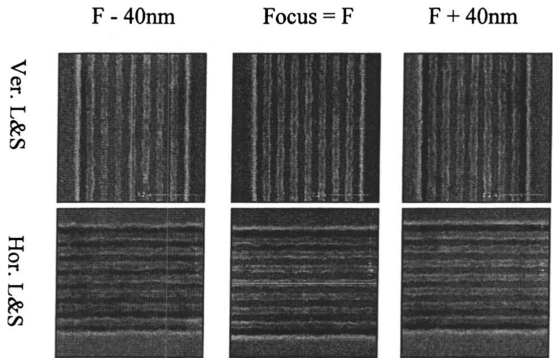

FIG. 1. Vertical and horizontal dense 32 nm half-pitch lines and spaces through focus. [Resist: Rohm & Haas XP-5271i (MET-2D); thickness: 90 nm; dose: ~25 mJ/cm^2; imaging setting: NA=0.25, σ=0.5 conventional.]

Recently EUV source power has been improved by more than an order of magnitude, increasing the Alpha Demo tool productivity to more than two wafers/hour. Imaging results are shown in Figs. 1 and 2. Note in Fig. 2 that contact holes at the edge and center have been printed without any optical proximity correction—this is possible, thanks to the high k_1 value of EUV (k_1=0.56 for 30 nm half-pitch, λ=13.5 nm, and NA=0.25). Measured overlay with the tools was 7.4 nm [μ+3σ] with the tool-to-itself and 11.2 nm [μ+3σ] with the tool-to-dry 193 nm scanner. Overlay defines the position of one image with respect to an image printed on a previous layer. It is measured by optical metrology, determining the relative position of markers printed in two layers with a predefined offset. State-of-the-art 193 nm lithography shows tool-to-itself overlay of 6 nm.[7] However, since the Alpha Demo tools were never optimized for overlay performance, and the vacuum environment is advantageous for interferometric control systems (no air turbulence), we can expect production EUV tools to perform better than today's 193 nm systems.

The two Alpha Demo tools have provided tool makers with essential EUV know-how. Moreover, they are currently instrumental in developing EUV infrastructure, including mask making and resists.

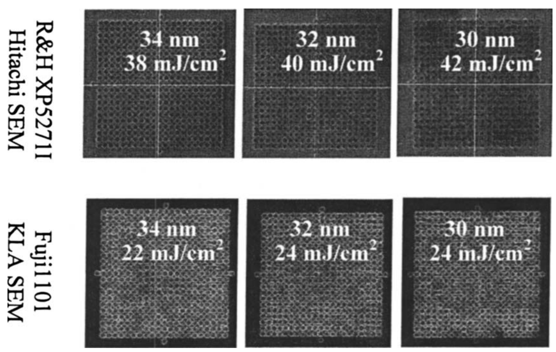

FIG. 2. Contact holes at 34–30 nm half-pitch (exposure dose is indicated in mJ/cm^2).

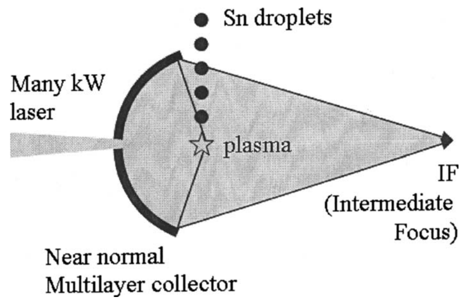

FIG. 3. LPP source.

III. CRITICAL EUV LITHOGRAPHY ISSUES

A. Source

Two types of EUV source are being developed based on laser produced plasma (LPP) and discharge produced plasma (DPP).[6] Figure 3 schematically shows the LPP source in which a multikilowatt CO_2 laser is focused onto a Sn droplet. After evaporation and ionization of the Sn droplet, hot plasma of a few tens of eV is created and emits light mainly in the EUV spectrum.[7] This radiation strikes a multilayer-coated collector mirror at a near perpendicular angle, where it is reflected to a point (see Fig. 3) called the intermediate focus. This is a separation point between the rather dirty source collector module and the clean illumination and projection optical chambers. Critical issues are Sn deposition on the collector and collector sputtering by Sn ions with energies of several keV and maintenance of spectral purity (contamination is caused by reflection and scattering of 10 μm CO_2 laser light and the deep ultraviolet component of the plasma-emitted radiation).[8]

Figure 4 schematically shows the other kind of EUV source based on a discharge produced plasma. Here, an electric current between Sn coated anode and cathode generates a Sn plasma. Due to self-pinching effect, the plasma is heated when the Lorentz force contracts the plasma. A multishell grazing incident collector reflects the light into the intermediate focus. A set of blades, so-called foil traps, prevents the Sn debris from reaching the collector. Critical issues are the Sn deposition on the collector and collector sputtering by Sn ions with energies of several tens of keV.

Several commercial source suppliers have credible roadmaps predicting outputs of more than 200 W by 2010 (see

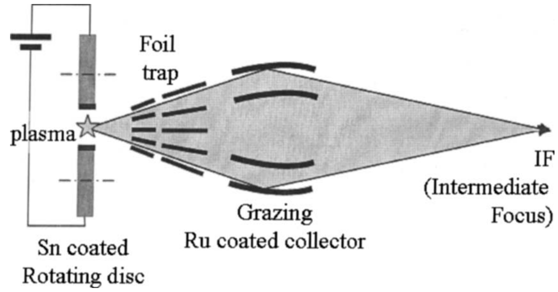

FIG. 4. DPP source.

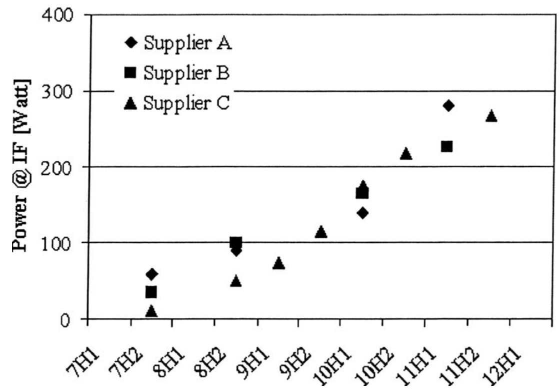

FIG. 5. EUV source power roadmap (2007 numbers are measured, 2008 and beyond are committed by EUV source makers).

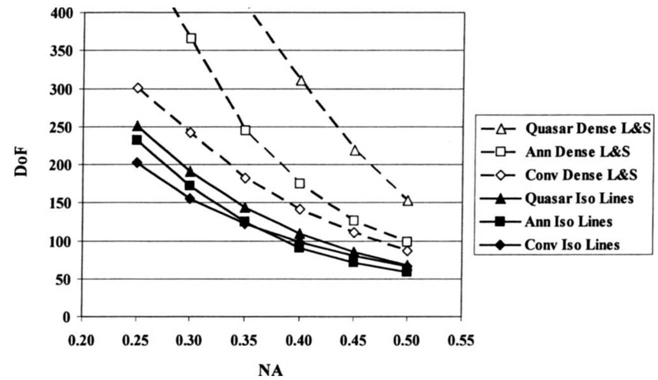

FIG. 7. Depth of focus (DoF) as function of NA for two types of features (dense lines and spaces; isolated lines) and three types of illumination (conventional, annular, and isolated).

Fig. 5). The highest powers reported today are typically obtained in burst mode. These powers will need to be maintained over hours in a module that includes EUV light collection and Sn debris mitigation.

B. Resist

Resist is a key parameter in the imaging performance of any lithography system. A critical parameter is the resist diffusion length (DL). Throughout this paper we characterize the DL as the standard deviation of the Gaussian function used to convolve the intensity profile. The exposure latitude and mask error factors have been calculated for various DLs and NAs. From this the obtainable resolution shown in Fig. 6 has been derived using minimum exposure latitude of 10% and a maximum mask error factor of 3.

From Fig. 6 one can derive that a NA $>$ 0.25 is required to obtain a resolution better than 20 nm. A known impact of increased NA is the decreased depth of focus (DoF). Figure 7 shows how the decreased DoF can be compensated when using advanced illumination modes. This is particularly the case when imaging dense lines and spaces.

Figure 8 shows progress in imaging ability over recent years. In particular, the more sensitive resists have shown significant progress. State-of-the-art resist with an E_{size} equal to 18 mJ/cm^2 has printed 24 and 22 nm dense lines and spaces with 4 nm line width roughness.[9]

C. Mask

The mask has to meet many requirements simultaneously, but as Fig. 9 shows, mask defectivity is most critical (e.g., champion data do not meet the requirement for feature size of 60 nm—30 nm is needed). In addition to making a defect free mask, one should also be able to store and handle masks without contamination. Here an industry-wide effort has resulted in a dual-pod proposal. This has demonstrated the ability to cope with multiple handlings of reticles—in and out of the vacuum—without adding particles.[10,11] Another critical aspect of the EUV mask is inspection. At present, printed wafers can be inspected for defects and repetitive defects can be ascribed to a mask. In the future, the EUV infrastructure will need mask inspection tools.

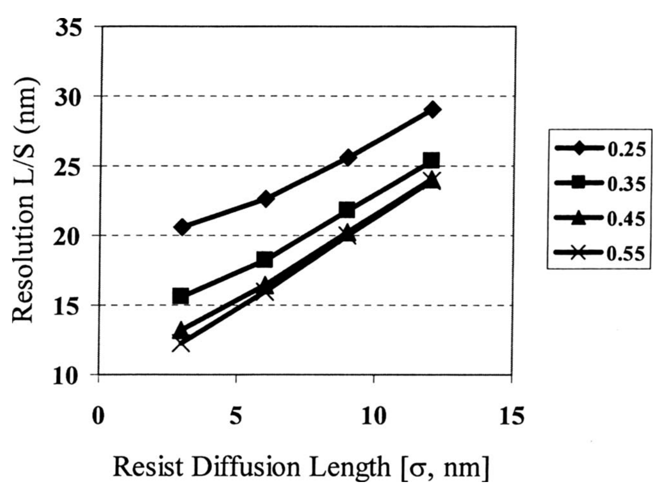

FIG. 6. Achievable resolution as function of resist diffusion length calculated for NA=0.25–0.55.

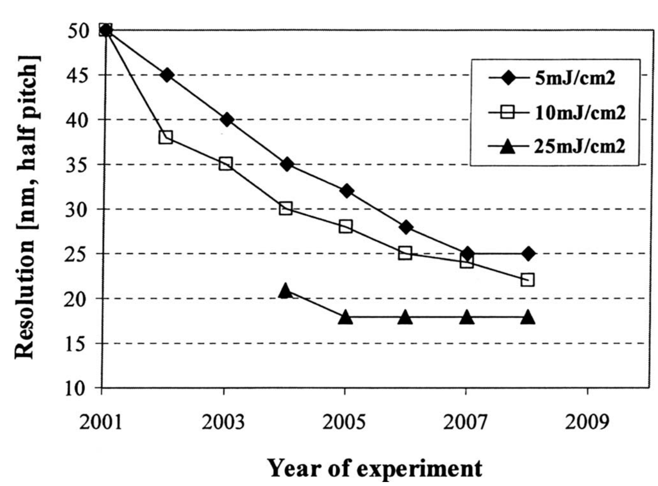

FIG. 8. Progress in resolution of EUV resists.

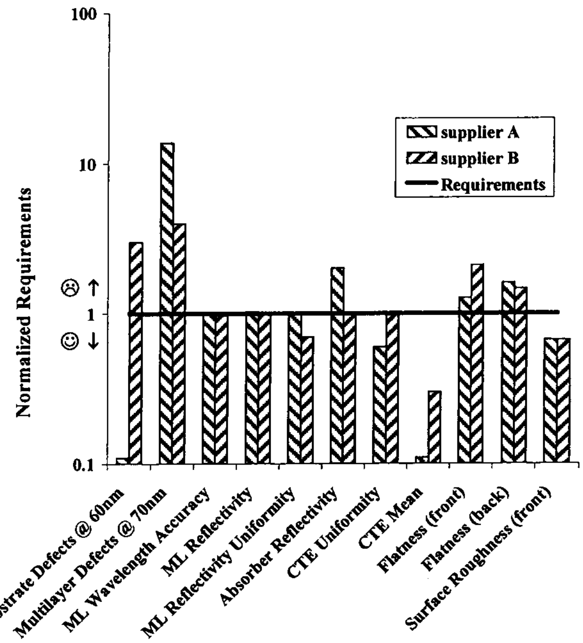

FIG. 9. Best data observed to date relative to specification of EUV mask blanc requirements for two suppliers.

IV. EXTENSION

As shown in Table I, one of the prime advantages of EUV is its ability to extend optical lithography to resolutions well beyond 22 nm half-pitch. The most straightforward way to extend EUV is to increase the NA of the lens. Today's Alpha Demo tool has six-mirror projection optics. The NA of this type of system could be extended to 0.3–0.35; the limiting factor will be apodization due to spread of incident angles on the mirrors' multilayer coatings. Using obscured designs (where the center of the pupil does not contain light), one can obtain slightly higher NAs while staying at six mirrors. If one adds two mirrors, at the expense of 50% additional light loss, and using an obscured design, one can obtain an NA of about 0.70. Figure 10 summarizes the various options as presented by W. Kaiser of Carl Zeiss during the SPIE 2008 microlithography conference.

V. SUMMARY AND CONCLUSION

Two full-field Alpha Demo tools have provided significant knowledge of how to build commercial EUV tools and are now being used to develop EUV infrastructure. Design and realization of next-generation preproduction tools is now well under way.

Several EUV source suppliers have demonstrated a steep increase in (burst-) power outputs. The next step will be to obtain EUV power out of integrated modules for extended periods of time. Six mirror optic designs can be produced to extend the NA of EUV systems well beyond 0.3.

In conclusion, EUV is on track and expected to be launched at the 22 nm node. Moving to obscured optical system designs with eight mirrors will enable NA values beyond 0.7 which, in combination with advanced illumination, will extend EUV beyond 11 nm half-pitch.

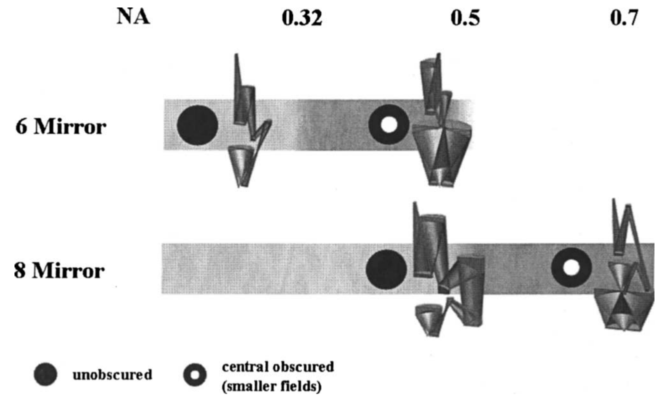

FIG. 10. Solutions for EUV projection optics.

[1]D. G. Flagello *et al.*, Proc. SPIE **5040**, 139 (2003).
[2]J. de Klerk *et al.*, Proc. SPIE **6520**, 65201Y (2007).
[3]See https://www.sematech.org/8352/pres/D2_Survey_Results.pdf.
[4]See http://www.itrs.net/Links/2006Update/FinalToPost/08_Lithography2006Update.pdf.
[5]H. Meiling *et al.*, "First performance results of the ASML alpha demo tools," Proceedings of the SPIE Symposium on Emerging Lithographic Technologies X, 2006 (unpublished), Vol. 6151.
[6]K. Ota, Y. Watanabe, V. Banine, and H. Franken, in *EUV Sources for Lithography*, edited by V. Bakshi (SPIE, Bellingham, 2005), Vol. 149, Chap. 2, p. 27.
[7]E. R. Kieft, Phys. Rev. E **71**, 026409 (2005).
[8]Vadim Banine, Proceedings of the EUVL Symposium, Sapporo, 2007 (unpublished).
[9]FijiFilm private communication.
[10]Long He, Stefan Wurm, Phil Seidel, Kevin Orvek, Ernie Betancourt, and Jon Underwood, Proc. SPIE **6921**, 69211Z (2008).
[11]Mitsuaki Amemiya, Kazuya Ota, Takao Taguchi, Takashi Kamono, Youichi Usui, Tadahiko Takikawa, and Osamu Suga, Proc. SPIE **6921**, 69213T (2008).