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C. R. Physique 7 (2006) 875–886
Comptes Rendus Physique
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Ultimate lithography/Lithographie ultime

EUV lithography

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Available online 20 November 2006

Abstract

Extreme ultraviolet lithography (EUVL) technology and infrastructure development has made excellent progress over the past several years, and tool suppliers are delivering alpha tools to customers. However, requirements in source, mask, optics, and resist are very challenging, and significant development efforts are still needed to support beta and production-level performance.

Some of the important advances in the past few years include increased source output power, tool and optics system development and integration, and mask blank defect reduction. For example, source power has increased to levels approaching specification, but reliable source operation at these power levels has yet to be fully demonstrated. Significant efforts are also needed to achieve the resolution, line width roughness, and photospeed requirements for EUV photoresists.

Cost of ownership and extendibility to future nodes are key factors in determining the outlook for the manufacturing insertion of EUVL. Since wafer throughput is a critical cost factor, source power, resist sensitivity, and system design all need to be carefully considered. However, if the technical and business challenges can be met, then EUVL will be the likely technology of choice for semiconductor manufacturing at the 32, 22, 16 and 11 nm half-pitch nodes. ***To cite this article: K. Kemp, S. Wurm, C. R. Physique 7 (2006).***

Résumé

Lithographie EUV. Le développement de la technologie et de l'infrastructure relatives à la lithographie en ultraviolet extrême (EUVL) a fait d'excellents progrès ces dernières années et les fournisseurs d'équipements livrent des machines alpha à des clients. Cependant les exigences sur la source, le masque, l'optique et la résine sont des défis difficiles et des efforts significatifs dans les développements sont encore nécessaires pour permettre des performances au niveau d'équipements bêta ou de production.

Parmi les quelques avancées importantes de ces dernières années on compte la puissance de sortie accrue de la source, le développement et l'intégration de l'équipement et du système optique, ainsi que la réduction des défauts des blancs de masque. A titre d'exemple la puissance de la source a été augmentée à des niveaux approchant les spécifications, mais opérer la source de manière fiable à ces niveaux de puissance n'a pas encore été complètement démontré. Des efforts significatifs sont aussi nécessaires pour satisfaire les exigences sur les photo-résines EUV en termes de résolution, de rugosité de trait et de photosensibilité.

Le coût de possession et la capacité à étendre la technique à des nœuds futurs sont des facteurs clés pour déterminer les perspectives d'insertion de l'EUVL en production. Puisque le débit de plaques est un facteur critique dans les coûts, la puissance de source, la sensibilité de la résine et la conception du système ont besoin d'être tous pris soigneusement en considération. Cependant, si les défis techniques et commerciaux peuvent être relevés, l'EUVL sera alors le choix technologique probable pour la fabrication de semiconducteurs pour les nœuds aux demi pas de 32, 22, 16 et 11 nm. ***Pour citer cet article : K. Kemp, S. Wurm, C. R. Physique 7 (2006).***

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doi:10.1016/j.crhy.2006.10.002

Keywords: EUV lithography; EUV source; EUV mask; EUV optics; EUV resist

Mots-clés : Lithographie EUV ; Source EUV ; Masque EUV ; Optique EUV ; Résine EUV

1. Introduction

Extreme ultraviolet lithography (EUVL) is an optical lithography technology that has many similarities with conventional optical lithography. The optical imaging process follows Rayleigh's laws, and EUVL systems make use of reduction optics, mask and wafer scanning, and alignment and focusing architectures that are similar to those found in current optical exposure tools. In addition, the lithography process builds largely on the experience of today's semiconductor fabrication processes. A major attraction of EUVL is that it is an extendible technology that can likely support patterning down to the 16 nm half-pitch (hp) node using binary masks and to the 11 nm hp node using more advanced mask types.

However, there are some significant differences between conventional optical lithography and EUVL. Many of these differences are a result of the very short wavelength light—13.5 nm—used in EUVL. Since all materials absorb EUV radiation, special reflecting optics with multilayer Bragg reflectors and extremely high precision finishes must be used. These reflecting optics are somewhat inefficient, resulting in an approximately 30% loss at each mirror. This limits the practical number of optical elements that can be used and dictates the use of aspheric surfaces, making figure and finish specifications even more difficult to achieve. The photomasks used for EUVL are also reflective, making the optical system non-telecentric since the mask is illuminated slightly off the normal optical axis. New types of plasma light sources are required to generate the short wavelength EUV light, and wafers must be exposed under vacuum to minimize EUV intensity losses by gaseous absorption and contamination or oxidation of the optical elements.

Most of the early work on EUVL focused on meeting the challenges just described, and many of the EUVL development efforts today are directed towards enabling the EUVL infrastructure and commercializing the technology so that it can be implemented by semiconductor device manufacturers later in this decade.

2. A short history of EUVL

Early concepts for EUVL emerged from research in Japan and the U.S. during the 1980s using what were then referred to as 'soft X-rays' in the 10 to 30 nm range. The first proposals to use EUV radiation for all-reflective projection lithography were made in 1988 by groups from Lawrence Livermore National Laboratories (LLNL) [1] and Bell Laboratories [2]. In 1989, a group from NTT demonstrated imaging of 0.5 μm features [3], and the first nearly diffraction-limited imaging of 50 nm features was accomplished in 1990 by Bell Laboratories [4]. The first EUVL system using a compact laser-produced plasma source [5] produced images at Sandia National Laboratories (SNL) in 1991, and in 1996 SNL fabricated the first functioning device patterned with EUVL [6] using a microstepper developed in collaboration with Bell Laboratories.

In the mid to late 1990s, several industry consortia started working on EUVL technology research and development. The Extreme Ultraviolet Limited Liability Company (EUV LLC) was formed in the US in 1997 to develop key EUV component technologies through close cooperation among six semiconductor manufacturers, three national laboratories, and several other industry partners [7]. The EUV LLC effort culminated in building the first EUVL full field tool prototype that produced its first full field images in early 2001 [8]. International SEMATECH started an EUVL program in 1998 to support mask modeling, microstepper optic development, and other topics [9]. SEMATECH's EUV program has since built up unique capabilities critical to EUV infrastructure development, including a Mask Blank Development Center (MBDC) and Resist Test Center (RTC) in Albany, New York [10,11]. The International Venture for Nanolithography (INVENT) consortium, also in Albany, New York, has recently started working on EUVL and received an EUV alpha tool in 2006.

In 1998, the European research program Extreme UV Concept Lithography Development System (EUCLIDES) was formed to evaluate EUVL. It focused on mirror substrates, high reflectivity multilayer coatings, vacuum stages, and a comparison of plasma and synchrotron EUV sources. The French PREUVE program was also initiated in 1999 with a focus on developing a 0.3 numerical aperture (NA) microfield exposure tool, EUV sources, optics, multilayers, mask and resist modeling, and defect metrology. The PREUVE and EUCLIDES programs subsequently transitioned into the European MEDEA+ program [12]. In addition, IMEC in Leuven, Belgium, has begun an EUVL program and received an EUVL alpha tool in 2006 [13].

The Japanese Association of Super-Advanced Electronics Technologies (ASET) program was also established in 1998 [14]. The EUV portion of the ASET program focused on multilayer, mask, resist, and process development. The ASET program was later joined by the Extreme Ultraviolet Lithography System Development Association (EUVA) program [15], and recently SELETE [16] has started its own EUV program and expects to install an EUVL alpha tool in 2007.

The combined efforts of research consortia, semiconductor equipment manufacturers, and other infrastructure suppliers have helped to position EUVL as a primary contender for volume manufacturing of semiconductor devices at the 32 nm hp node and beyond [17]. However, it is important to recognize the significant advances that have been made in extending 193 nm lithography to sub-wavelength imaging using sophisticated optical proximity correction (OPC) methods; increased NA; and more recently, immersion imaging. Although some issues with 193 nm immersion lithography remain, the technology is generally assumed to be the likely solution for volume manufacturing at the 45 nm hp node, and it may possibly be extended further using higher refractive index fluids, double exposure lithography (DEL), and 193 nm double patterning lithography (DPL) techniques [18].

3. EUVL technology status

Detailed discussions of EUV tools and technology can be found in the literature [7,19–21]. This section provides a brief overview of the key technology components with emphasis on their current development status and the remaining issues that must be resolved to ensure successful introduction of the technology for volume manufacturing in the semiconductor industry.

3.1. EUV optics

The projection optics system is at the heart of the performance of an EUVL tool, and tool and optics manufacturers are working hard to develop and improve manufacturing technologies to achieve the required specifications. A key challenge in EUV optics manufacturing is to simultaneously meet the stringent figure and finish requirements of the reflecting surfaces. The total system wave front error (WFE) specification for a 0.25 NA six-mirror projection optic system will be $\leqslant 0.27$ nm rms. Assuming that surface figure errors in individual mirrors are uncorrelated, the figure specification for each mirror will be $\leqslant 0.08$ nm rms. In addition, the WFE must remain stable over the lifetime of the optics and may need to be monitored in the field. Similarly, a flare requirement of less than 7–8% for production tools demands tight control of mid-spatial frequency roughness (MSFR) on the optic surfaces without compromising the surface figure. For future EUV tool generations with eight-mirror optics, these specifications will be even more challenging.

The availability of accurate and reproducible metrology techniques for individual mirrors and assembled projection systems is also critical. WFE metrology systems for assembled EUV optics have been developed using variations of at-wavelength phase shifting diffraction interferometry (PSDI) and lateral shearing interferometry (LSI) [22]. Visible light interferometry has also been used to overcome the logistical difficulty of relying on synchrotron-based at-wavelength interferometry systems. Some progress has been made toward developing coherent EUV laser sources [23], which may prove useful for constructing standalone at-wavelength interferometry tools or for implementing in situ monitoring systems within EUV tools.

Another major challenge for EUV projection optics systems is reflectivity degradation. EUV optics must meet a requirement of less than 1% non-recoverable reflectivity loss during 30 000 light-on hours, equivalent to a 10-year operating lifetime. Because the projection optics cannot be heated to achieve ultra-high vacuum conditions (as this would damage the reflective multilayers), they must operate in an environment with water vapor and hydrocarbons present. Under EUV exposure in these conditions, the optics can be subject to recoverable and non-recoverable reflectivity losses: water adsorbed on surfaces may be dissociated by EUV photons or by secondary electrons generated by the photons, leading to oxidation of the reflecting surface and a non-recoverable reflectivity loss. The dissociation of adsorbed hydrocarbons may also result in elemental carbon buildup, although this may be removed through reactions with oxygen or hydrogen and evidence suggests that water vapor and hydro-carbon partial pressures can be optimized for a given EUV photon flux such that carbon buildup and oxidation are balanced. However, if environmental control of individual mirrors or in situ mirror cleaning technologies should be needed to maintain optics performance, these would add significant technical challenges and cost to the tool design.

Experimental data on EUV optics lifetime are quite sparse, with the longest duration tests published to date yielding an estimated lifetime of 726 light-on hours [24]. Although progress is being made in understanding the fundamental material science and surface physics/chemistry that govern EUV optics lifetime [25,26], the implementation of this knowledge in engineering solutions that will achieve the 30 000 hour lifetime has yet to be demonstrated. In addition, tool manufacturers have begun to consider the potential need to monitor the reflectivity of EUV optics in situ. Until more convincing data become available, the lifetime requirement for EUV optics has to be seen as extremely challenging.

3.2. EUV sources

EUV light in the 13.5 nm wavelength band is produced by hot plasmas of a target material, usually Xe, Sn, or Li [20]. The target material is excited either by a high power laser in laser produced plasma (LPP) sources or by an electrical discharge in discharge produced plasma (DPP) sources. There are other methods of producing EUV radiation in the 13.5 nm range; for example, low power laser-fiber sources could be used in metrology applications such as at-wavelength inspection of EUV mask blanks, EUV optics interferometry, aerial image measurement systems, or electron density measurements in source plasmas [20,27].

Fig. 1 summarizes the progress in EUV source power over the past 5 years. By convention, power is measured as the EUV power flux in a 2% bandwidth window around the 13.5 nm wavelength at the intermediate focus (IF) position that follows the collector optic. The best Sn DPP sources today can deliver peak power of around 80 W when operated in burst mode; they are currently in a leading position to achieve the 115–180 W requirement for the first production generation of EUV exposure tools. The choice of target material is significant because the conversion efficiency (CE) of electrical or laser input power to generated EUV power is a strong function of the target. Specifically, Sn and Li (approximately 5% and 2% CE) have been demonstrated to produce significantly higher output than Xe (approximately 1% CE), which was used in most early source development work. On the other hand, Xe gas is considerably easier to manage in the source than solid Sn or Li target materials and produces much less damaging debris.

The 115 W power specification assumes that EUV photoresists with 5 mJ/cm^2 sensitivity will be available to support an exposure throughput of around 100 wafers per hour. Because a 5 mJ/cm^2 resist may not be available in time to support the first production tools, the power specification has been raised by one supplier to 180 W at IF. Further complicating the source power requirement are two other issues that must be addressed: radiation produced by

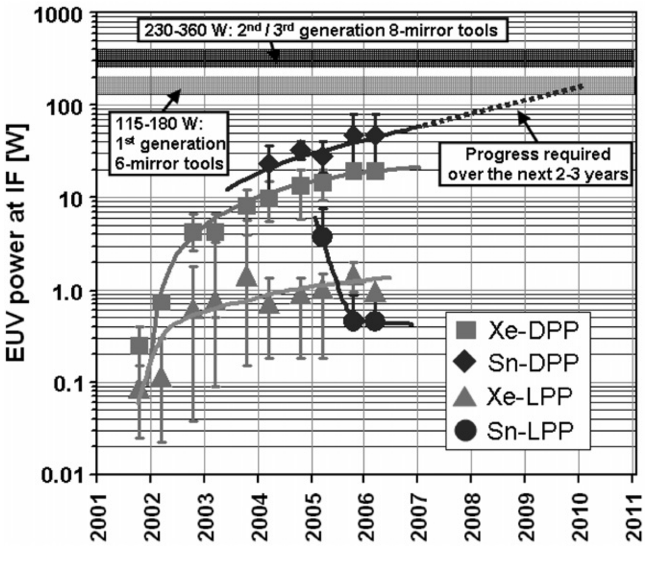

Fig. 1. Performance data for EUV sources reported at SEMATECH EUV source workshops [28]. The data points show EUV power levels at the IF for different source types and target materials.

the source that is outside the 2% bandwidth, the so-called out-of-band (OOB) radiation, must be suppressed to prevent image contrast loss in the resist. One possible solution is to implement a spectral purity filter (SPF) at or near the IF position; however, any such filter will need to be highly selective to avoid attenuating the in-band EUV power. The second requirement is that high energy debris from the plasma source must not degrade the collector optic. This may require the use of a debris filter or other mitigation device that may also increase the EUV source power requirement.

Despite the progress illustrated in Fig. 1, it is also apparent that the rate of improvement is decelerating. For DPP sources, this is largely due to the increasing heat load generated at the discharge electrodes. Some innovative solutions such as rotating electrodes [29,30] have been proposed, but the problem of heat loading on the nearby collector optic, which is difficult to cool given its construction and location inside the vacuum environment, remains.

For LPP sources, the availability of affordable high power lasers is a problem. If over the next several years, diode-pumped solid state lasers should become significantly less expensive and more reliable, or if some innovation in efficient laser power delivery were to be demonstrated, then there could be a resurgence of interest in LPP sources.

With respect to EUVL readiness for manufacturing, the major concern with EUV sources is no longer just achieving higher peak power, but also solving source reliability issues and improving cost of ownership. EUV sources with power levels exceeding 60 W need to operate continuously for several months with uptime and cost of ownership comparable to that of current optical lithography sources. This performance needs to be achieved in the next 1 to 2 years to demonstrate a credible path to meeting the requirements for volume manufacturing later this decade.

3.3. EUV masks

EUV masks are made by depositing a multilayer Bragg reflector film stack on an ultra low thermal expansion glass substrate, followed by a series of buffer, absorber, and anti-reflecting layers. The absorbing layers are subsequently patterned using conventional optical mask-making technology to generate features with high reflection contrast at the EUV wavelength. Industry specifications have been published for both the substrate (SEMI P37-1102 [31]) and the unpatterned mask blank (SEMI P38-1103 [32]).

To prevent defects from being imaged on the wafer, the mask needs to be manufactured and maintained free of defects throughout its useful lifetime. This requires that the substrate, reflecting multilayer, and absorber stack are produced with zero defects. Fortunately over the past several years, a substantial amount of work has been directed at developing defect-free EUV masks. For example, Fig. 2 shows the progress in reducing mask blank defects at SEMATECH as well as the remaining progress needed to meet the manufacturing requirement of less than 0.003 defects/cm^2 at $\geqslant$25 nm. Some of the remaining challenges include the development of affordable manufacturing processes for defect-free substrates and thin film deposition, defect inspection, cleaning and repair technologies, and an EUV mask-handling infrastructure that builds on standards currently under development [33].

EUV mask substrates must meet stringent specifications for coefficient of thermal expansion (CTE), flatness, defectivity, and surface micro-roughness. The materials that have been developed for EUV mask substrates currently have CTE values in the region of 10 to 15 ppb/°C; these need to be improved to less than 5 ppb/°C. Flatness as measured by the peak-to-valley surface deviation is currently about 2X larger than the requirement of 50 nm, although local slope variation (another key measure of flatness) has already been demonstrated to meet the production specification [34]. Surface micro-roughness is acceptable using current polishing processes, but new polishing processes developed to achieve flatness or reduce defects may compromise this performance. Substrate suppliers have reduced substrate defect levels considerably and have simultaneously developed cleaning technologies that can efficiently remove particles as small as 50 nm [35]. Pit-type defects in the substrate remain a significant challenge, and attempts are being made to address this by developing multilayer 'smoothing' techniques that can reduce their impact on the final mask topography.

Several approaches have been proposed to reduce the impact of defects on EUV mask blanks. Defect avoidance and mitigation include intelligent absorber pattern placement to cover existing defects and 'defect-OPC' to reduce defect printability. If these techniques are combined with other defect repair techniques, then usable mask blank yields in the range of 60 to 70% could be achieved even with native defect levels at 0.03 defect/cm^2. This strategy would imply higher mask costs initially, but it would allow early introduction of the technology while defect reduction efforts continued.

Effective defect control also requires highly sensitive defect inspection capability. Today this is done using sophisticated visible light inspection tools that typically are capable of finding 50 to 60 nm defects. More sensitive tools will

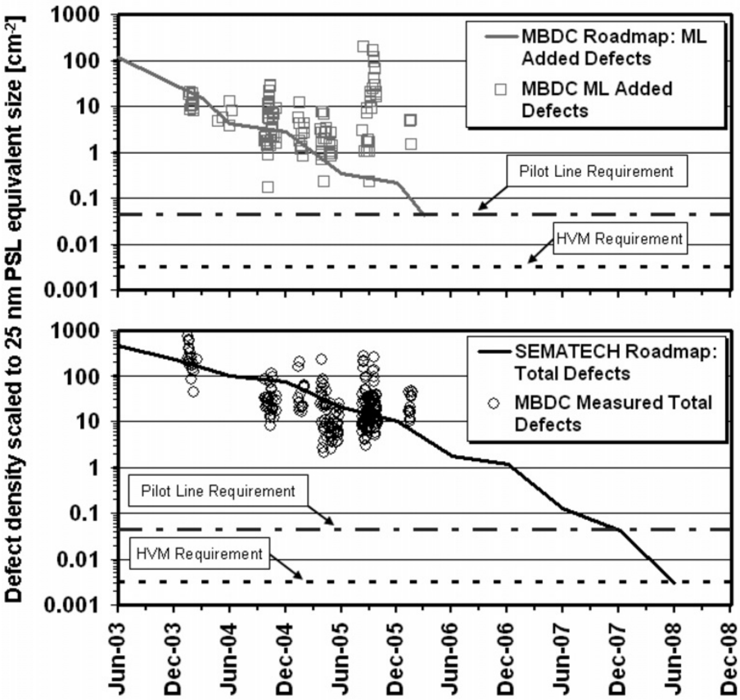

Fig. 2. SEMATECH Mask Blank Development Center (MBDC) progress in mask blank defect reduction.

be required to achieve the 25 nm defect sensitivity required for EUV masks at the 32 nm hp node, but there is also a concern that visible light tools may not effectively capture some defects that print using EUV light because these tools do not test the resonant structure of the multilayer stack. For example, one study showed that a 25 nm spherical defect buried under a 40-bilayer Mo/Si multilayer produced a surface bump 1.5 nm high and 65 nm wide. Although this defect could not be detected by a visible light tool, it was sufficient to produce a 20% critical dimension (CD) change in a printed line [36–38]. In addition, there is some evidence that the laser power used in visible light inspection may damage the thermally sensitive EUV multilayer stack. Therefore, at-wavelength EUV inspection may ultimately be required to find defects that visible inspection techniques cannot detect. Although a few experimental at-wavelength inspection tools have been built, it would likely require several years to produce a commercial tool.

The patterning of EUV mask absorber layers is expected to use conventional e-beam writing, dry etch, inspection, and repair technologies. One significant advantage of the high imaging resolution of EUVL is that masks will not require the extensive OPC that is currently used for optical masks (although some correction for pattern-dependent EUV flare may be required). Without extensive OPC, the cost and cycle time associated with patterning EUV masks are expected to be significantly less than that of advanced optical masks. However, an issue related to chucking EUV masks during the patterning process still needs to be addressed. Because the EUV imaging path is not telecentric, EUV masks must be held almost perfectly flat to minimize pattern distortion across the imaging field. Exposure tools will use electrostatic chucks to hold the mask flat under vacuum; therefore, mask writer and pattern placement metrology tools will need to either hold the mask electrostatically or make complex coordinate corrections to account for distortions introduced by other chucking methods.

Once defect-free EUV masks are available, they must be protected from environmental defects and contamination. Optical masks use a fixed, transparent pellicle to keep particles away from the imaging surface of the mask. Although similar approaches have been attempted for EUV masks [39], the significant absorption losses during exposure would need to be offset by even further increases in source power. Therefore, a solution has been proposed that uses a pellicle that is temporarily attached to the mask and removed only during exposure inside the EUVL tool. Several variations of this removable pellicle concept as well as modifications to standard mask carrier designs have been proposed and are under evaluation [33]. As shown in Fig. 3, at least one of those solutions used in conjunction with automated handling equipment has demonstrated a >100X reduction in handling-related defects compared to an unprotected

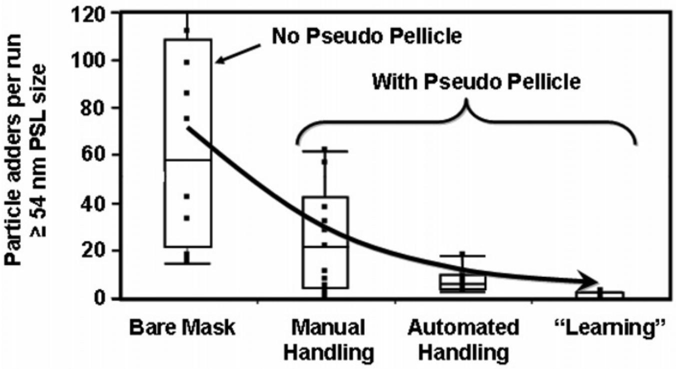

Fig. 3. Pseudo pellicles combined with automated handling demonstrated a >100X reduction in handling added defects [40].

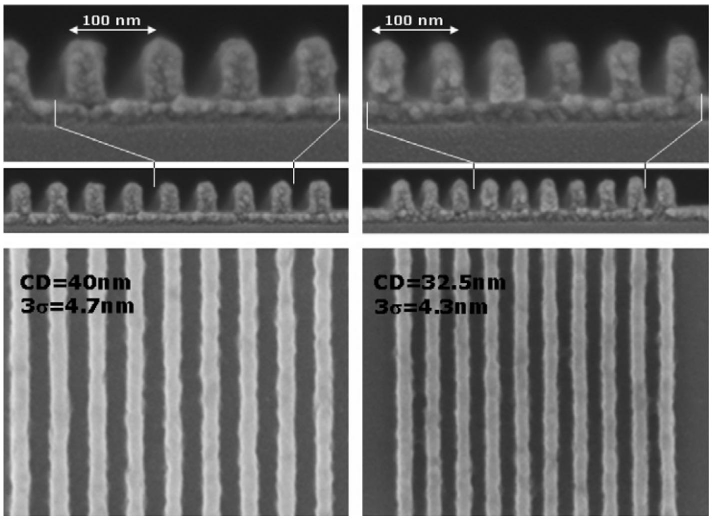

Fig. 4. Resist images recorded with the SEMATECH MET; pictures courtesy of AMD [41].

mask [40]. Common standards for EUV mask storage and shipping carriers are also being developed to avoid costly incompatibilities among exposure, inspection, and other mask-handling tools [33].

In summary, good progress has been made in all aspects of EUV mask technology. To achieve the manufacturing requirements for the 32 nm hp node and beyond, these current focused efforts of industry and consortia need to be continued. Defect reduction, avoidance, and repair strategies will be particularly critical for the technology to achieve acceptable mask yields.

3.4. EUV photoresists

The primary challenge for EUV resists is to simultaneously meet the specifications for resolution, line edge roughness (LER), and photospeed [17]. EUV resists also need to meet stringent outgassing specifications so that they do not contaminate EUV projection optics. The resolution and LER requirements apply to 193 nm immersion resists as well, but the sensitivity challenge is specific to EUVL because of the limited power available from EUV sources.

The best EUV resist performance demonstrated to date for 32.5 nm dense lines and spaces is 4.3 nm 3σ LER and 11 mJ/cm^2 sensitivity [41]. A cross section of this resist patterned using a 0.3 NA microfield exposure tool (MET) at Lawrence Berkeley National Laboratory is shown in Fig. 4. Resolution of approximately 28 nm with 4 nm LER has also been demonstrated for isolated lines using a resist with 8 to 9 mJ/cm^2 sensitivity [42].

A key problem is that resist suppliers require access to EUV exposure tools to make progress in developing new resist formulations, and until recently such access has been very limited. However, four 0.3 NA METs have become available within the past 2 years: one at SEMATECH in Albany, New York; one sponsored by SEMATECH at Lawrence Berkeley National Laboratory in Berkeley, California; one at Intel in Hillsboro, Oregon; and one at ASET in Atsugi, Japan. Synchrotron-based interference lithography (IL) tools have also been used to achieve high resolution EUV imaging.

It is not clear yet if the resist requirements for the 32 nm hp node can be fully met with current chemically amplified resist (CAR) platforms. If new chemistry platforms are required, their development will have to accelerate dramatically to have them ready for manufacturing insertion before the end of this decade. Ultimately, the development of improved EUV resists will require a fundamentally different level of understanding of the relevant physical, chemical, and electronic processes. For example, it has been widely acknowledged that secondary electrons play an important role in EUV resist exposure, but little work has been done to characterize secondary electron yield and energy distribution. It will probably be necessary to use such data, in conjunction with nano- and meso-scale modeling of resists, to develop EUV resists with faster, higher resolution and less LER.

3.5. Tool throughput

Throughput is both a technical and an economic issue, since EUVL can be commercially successful only if the processing throughput is sufficient to amortize the substantial tool, mask, and other processing costs. For this discussion, a simple throughput model can be used to examine the status of the technology and its impact on successive technology generations. Wafer throughput in wafers per hour (wph) is given by,

$$TP[\text{wph}] = \frac{3600\ \text{s}}{T_{\text{overhead}} + T_{\text{exp soure}}} = \frac{3600\ \text{s}}{T_{\text{overhead}} + \frac{E_{\text{wfr}}}{P_{\text{wfr}}}} \tag{1}$$

where T_{exposure} is the actual wafer exposure time in seconds and T_{overhead} includes the time to move, align, and focus the wafer, along with stage settling time and other losses incurred during the exposure process. E_{wfr} is the total energy required to expose the wafer, and P_{wfr} is the available EUV power at the wafer plane.

Fig. 5 illustrates the relationship between source power and T_{overhead} for a range of resist sensitivities at a 100 wph throughput. For example, the current power specification of 115 W at IF was derived for a six-mirror EUVL tool exposing a 5 mJ/cm^2 resist at 100 wph [43]. In this case, the exposure time is 9 s and T_{overhead} is 27 s. If a 10 mJ/cm^2 resist were to be used, then $\text{T}_{\text{exposure}}$ would double to 18 s and the throughput would drop to 80 wph. To maintain a 100 wph throughput for the 10 mJ/cm^2 resist, the EUV source power would need to be doubled to 230 W. Alternatively, a 30% improvement in T_{overhead} to 18 s would achieve the same goal. Clearly, reducing T_{overhead} provides

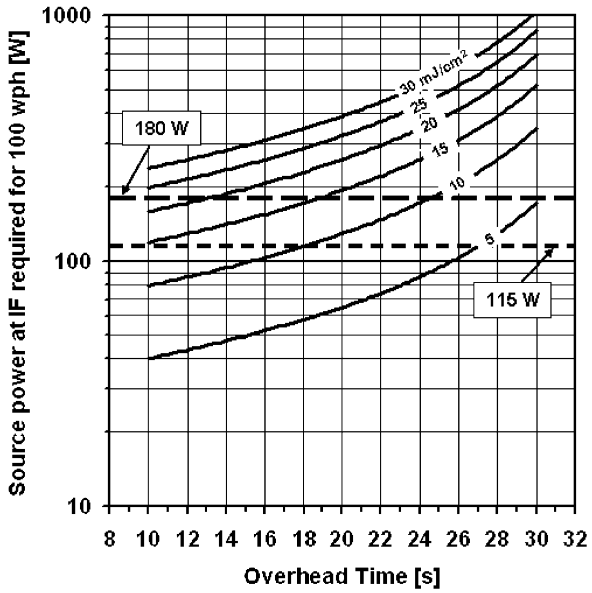

Fig. 5. Trade-off between exposure time and overhead time illustrated for a range of resist sensitivities.

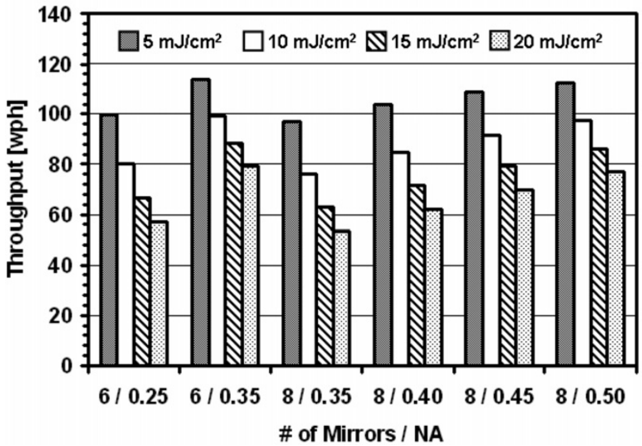

Fig. 6. Projection of system throughput for several EUV tool generations using four different resist sensitivities.

significant leverage for reducing the source power requirement. Even with 10 mJ/cm^2 resist sensitivity, 60 W source power, and a moderate improvement in tool overhead, it should be possible to achieve throughput of approximately 60 wph to support initial pilot production using EUVL.

It is also interesting to consider the impact of future lithography generations. To achieve higher imaging resolution, second or third generation EUV tools will likely be designed with higher NA optics which will require eight-mirror projection optics instead of the six-mirror systems used in first generation tools. Losses at the two additional mirror surfaces (each with 70% reflectivity) will increase the source power requirement by a factor of 2. Fortunately, light collected from the source increases as the square of the NA. Thus, if the source and collector optics are designed appropriately, the losses imposed by additional mirrors may be more or less offset by the higher numerical aperture design [44,45]. Fig. 6 shows the results of an analysis of system throughput for six different cases spanning several generations of tools and resist sensitivities from 5 to 20 mJ/cm^2 at a source power of 115 W indicating that it should also be possible to maintain throughput if the sources and illuminations systems can be designed appropriately.

The previous discussion suggests that an EUV throughput of approximately 100 wph is feasible if efforts to improve EUV source power, tool overhead time, and/or resist sensitivity are successful. Arguably the greatest risk to achieving 100 wph throughput is the problem of achieving resists having 5 mJ/cm^2 sensitivity together with the required resolution and LER. It is therefore imperative that efforts to increase source power and minimize tool overhead command a high level of attention. This will also allow resist suppliers to focus on meeting the increasingly aggressive resolution and LER requirements, while potentially opening up a broader range of materials that may be considered.

4. Outlook

Some of the critical issues facing the introduction of EUVL have been discussed. However, the ultimate decision to implement EUVL will also depend on the relative capabilities, costs, and risks associated with competing technologies. This section compares the lithographic potential of EUV with that of 193 nm optical immersion lithography, including variations that could extend its useful lifetime.

Two fundamental properties of an optical projection system are resolution (R) and depth of focus (DOF), as characterized by Rayleigh's equations [46],

$$R = k_1 \cdot \frac{\lambda}{\mathrm{NA}} \tag{2}$$

$$\mathrm{DOF} = \pm k_2 \cdot \frac{\lambda}{\mathrm{NA}^2} \tag{3}$$

where λ is the optical wavelength and NA is the numerical aperture of the projection system. The classical Rayleigh limits for k_1 and k_2 are 0.5. In practice, the ultimate resolution and depth of focus depend on the characteristics of the lithographic process, such as the contrast of the resist system and the extent to which various optical enhancement techniques (e.g., phase shifting, OPC, and off-axis and polarized illumination) are used [47,48]. Thus, the actual value of k_1 (as measured by the minimum half pitch of the printed feature) in leading-edge semiconductor manufacturing is in the region of 0.4 to 0.45 for random logic and 0.3 to 0.35 for highly repetitive layouts such as memory.

Eq. (2) also reflects the historical improvements in lithographic resolution that have been achieved by incremental reductions in wavelength and increases in NA; Eq. (3) also highlights the shrinking DOF and corresponding process latitude that have resulted from these advances.

4.1. The limits of 193 nm lithography

By interposing a fluid between the projection lens and wafer, immersion lithography allows the NA to be increased beyond the limit that is achievable in air. It also provides the advantage of increasing DOF proportional to the refractive index of the fluid [49]. A 193 nm water-based immersion lithography may be introduced for volume semiconductor manufacturing at the 65 nm hp node, with 1.2 NA optics providing a k_1 value of 0.40. At the 45 nm hp node, the maximum NA achievable using water as the immersion fluid is of 1.35, yielding a k_1 value of 0.31. A fluid with a higher refractive index could allow the NA to be increased up to 1.55 using conventional fused silica lens materials, providing a k_1 value of 0.36 at 45 nm hp. Assuming higher refractive index lens materials can be developed, 1.70 NA would yield a k_1 value of 0.28 at the 32 nm hp node. Very sophisticated optical enhancement techniques will probably be needed to realize this resolution in volume manufacturing.

Another possibility at the 32 nm hp node is to use two interleaved exposures at twice the targeted pitch. This would enable an effective k_1^{eff} value for the combined exposure that would be half the value of the k_1 for the respective single exposures. Two possible variations have been proposed: double exposure lithography (DEL) would use either a highly non-linear or a 'memoryless' resist to allow two exposures to be made before developing the resist, while double patterning lithography (DPL) would use two complete expose/develop/etch cycles to form the pattern [50]. Suitable resists for DEL do not exist yet, and DPL would effectively double the cost of the lithography process as well as require improvements in tool overlay capability. However, DEL or DPL could conceivably extend 193 nm optical lithography to the 22 nm hp node if used in conjunction with high index resists and lens materials. The effective resolution and k_1 or k_1^{eff} value of each of the above approaches are shown in Fig. 7 and compared with the corresponding resolution scenarios for EUVL.

4.2. EUV lithography limits

The situation is somewhat different for EUV, where resolution is achieved at a much shorter wavelength and relatively relaxed k_1 values. Thus the k_1 values for EUVL using 0.25 NA optics at the 45 and 32 nm hp nodes are 0.83 and 0.59, respectively. While 0.25 NA optics would also support development work at the 22 nm hp node with a k_1 value of 0.41, 0.35 NA optics would increase the k_1 value to 0.57 and potentially allow more power to be collected from the source. At the 16 nm hp node, 0.35 NA optics would yield a k_1 value of 0.41, and resolution to the 11 nm hp node is conceivable using 0.4 to 0.5 NA optics. However, at this point the DOF of EUVL (less than 75 nm) becomes a serious concern and optical enhancement technologies such as OPC and phase shifting will probably also be required.

4.3. Summary: technical and business challenges

As noted previously, selection of the appropriate technology at each node will depend on the technical status, cost, and perceived risk of each technology. Single exposure 193 nm immersion lithography appears to be feasible only up to the 32 nm hp node, at which point k_1 values are extremely aggressive even if suitable high refractive index, lens materials, and resist can be developed. Double exposure techniques provide a potentially more relaxed k_1 solution, but at a significant throughput and cost penalty.

Masks for 193 nm immersion lithography at the 32 nm hp node will also be a technical and cost challenge. Extensive OPC will be required, including new OPC techniques to address polarized illumination and the effects of mask topography. Extremely high NA imaging optics will be significantly larger and more difficult to manufacture than today's optics and much more expensive.

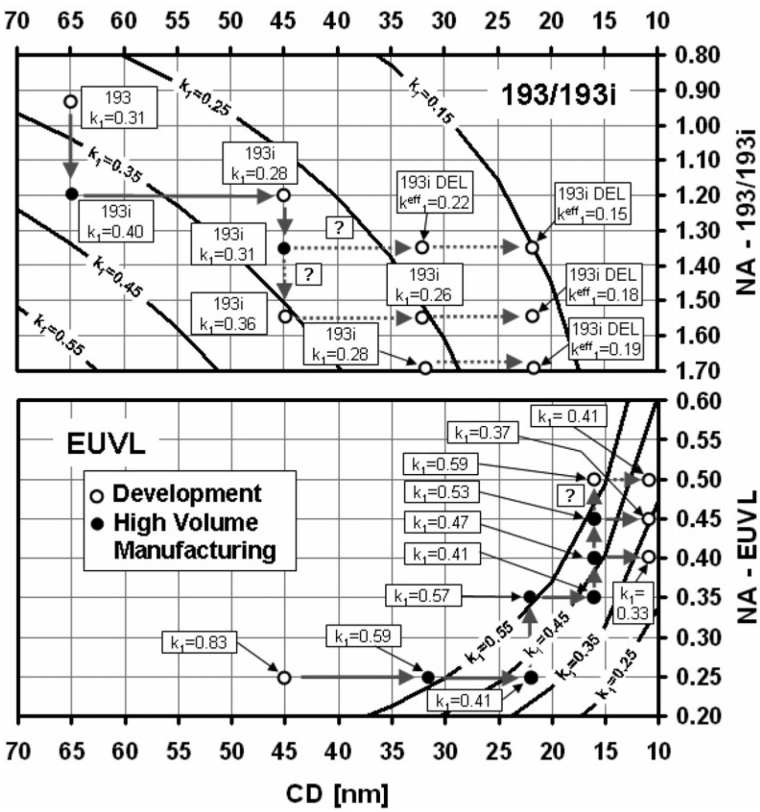

Fig. 7. Comparison of k_1 values for possible EUVL and 193/193i scenarios. EUVL will likely allow the industry to stay above $k_1 = 0.50$ down to 22 nm hp and above $k_1 = 0.40$ at 16 nm hp.

The successful introduction of EUVL requires continued progress in source power, resist resolution and sensitivity, mask defectivity, and optics lifetime. If these challenges can be overcome, EUV will likely be the technology of choice at the 32 nm hp node, with a clear path to the 11 nm hp node.

Acknowledgements

The authors would like to thank their colleagues in the SEMATECH Lithography Division: among them SEMATECH direct hires and assignees; employees of the SEMATECH member companies; and the principal investigators and their teams at the companies, research institutions, and universities with which SEMATECH is collaborating.

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