

EUV Lithography: State-of-the-Art Review

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Abstract: Although several years delayed than its initial plan, extreme UV lithography (EUVL) with 13.5nm wavelength has been finally implemented into high volume manufacture (HVM) of mainstream semiconductor industry since 2018. With the delivery and installation of ASML EUV scanners in those giant Fab players like Samsung, TSMC and Intel, EUV lithography is becoming a sort of industry standard exposure metrology for those critical layers of advanced technology nodes beyond 7nm. Although ASML NXE EUVL scanner is the only commercialized EUV exposure system available on the market, its development is the concentration of all essence from worldwide industrial and academic collaboration. It is becoming more and more important not only for fab runners but also for main stream fabless design houses to understand and participate the progress of EUVL. In this review, working principles, module structures and technical challenges have been briefly discussed regarding each EUV subsystem, including light source, reflection mirrors and system, reticle module as well as photoresist development. EUV specific issues of light intensity, defectivity within reflection system, line edge roughness (LER) and mask 3D effects have been focused respectively and promising solutions have been summarized as well.

Keywords: EUV lithography, EUV review, mask 3D, line edge roughness, EUV light source.

1. Introduction

The development and growth of semiconductor industry has been following Moore's law in recent 50 years, and it is fair to say that the continuous shrinking of transistors in microchips has been mainly driven by the development of photolithography technology^[1-3]. Since the appearance of the first G-line (436nm wavelength) step-and-repeat system, namely wafer stepper, in late 1970s, this exposure system quickly has become mainstream and dramatically promoted the capability and efficiency of photolithography^[4,5]. Due to the Rayleigh diffraction effect, smaller wavelength of light has to be adopted in order to get a reduced feature size with high resolution through a lens system, which makes a semiconductor device smaller. After jumping onto the fast lane of step-and-repeat system, the light source adopted in photolithography has been continuing switching from excimer laser for i-line (365nm)^[6], to krypton fluoride (KrF) excimer laser for 248nm deep ultraviolet^[7] and to argon fluoride (ArF) for 193nm wavelength in order to get even smaller feature size^[8,9]. On this track, 157nm wavelength of F₂ excimer laser was supposed to be produced to reach smaller half pitch than 65nm^[10,11]. However, wavelength is not the only factor to improve the resolution of smaller pitches. Numerical aperture, NA as the Acronym, plays another role by

the Rayleigh criterion:

$$R \text{ (smallest feature size)} = k_1 * \lambda / NA$$

where λ is the wavelength of the light used, NA is the numerical aperture of the system's lens and k_1 is known as the resolution factor and accounts for all other process variables. Furthermore, since $NA = n * \sin \alpha$, where α is the light incident angle and n is the refractive index of the medium surrounding the lens, and liquid has a larger n than air, an immersion ArF scanner was developed to reach a higher resolution for smaller features, in which immersion fluid (mainly water) is well controlled to stay between last lens and wafer surface in order to get higher NA^[12] (Figure 1). The first commercial tool with this innovative technology was built and shipped by ASML in 2006 which started to dominate the market since then. The cost-effective implementation of immersion ArF scanner in the industry killed further development of tools with 157nm wavelength.

The implementation of immersion ArF scanner, enhanced by RET (Resolution Enhancement Technology) and multi-patterning technologies enabled the industry to reach 10nm/7nm FinFET tech node with acceptable cost, efficiency and die yield. But what is next? To resolve lines (half-pitch) smaller than 7nm, quadruple patterning or even more masks need to be used only for one functional layer, which will dramatically increase the cost and process

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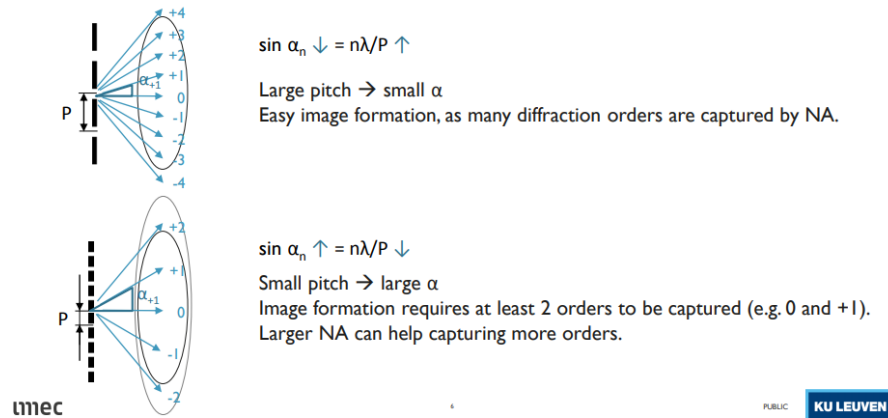


Figure 1. Illustration of Rayleigh criterion. Larger NA benefits smaller pitches. Courtesy of Vu Luong, IMEC^[14].

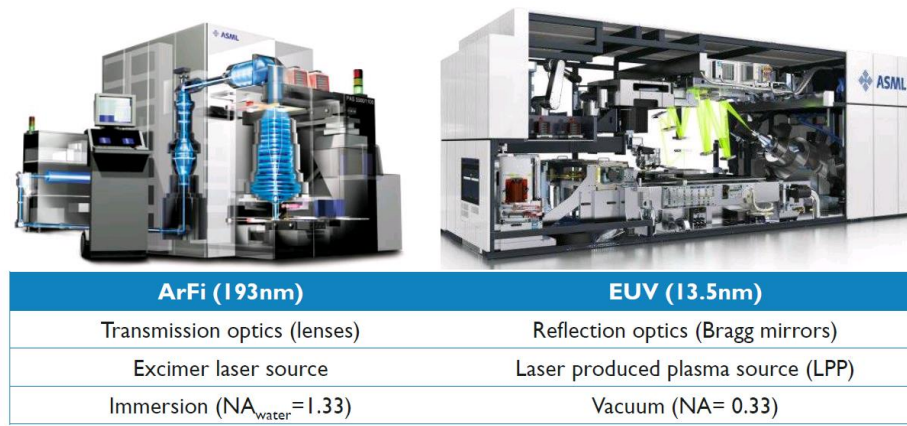


Figure 2. Comparison of an ASML ArF immersion scanner and an ASML EUV scanner. Courtesy of Vu Luong, IMEC^[14].

variation. The industry has to follow Rayleigh criterion again to push the exposure wavelength to the limit.

The industrialization of EUV lithography (EUVL) has been turned on since the turn of the 21st century and even earlier. Almost all key players from the industry and academic institutes have been involved in EUV light source development, Bragg mirrors with multi-coated layer, reflection system in vacuum, reflection reticle design and material development, EUV photoresist synthesis and optimization, contamination and defects reduction, DTCO (Design Technology Co-Optimization) and EDA tool development, as well as many other related engineering fields^[13]. Most of the accomplishments of research and development have been concentrated to the ASML NXE EUVL module, which began its journey of High Volume Manufacture (HVM)^[1,14] since 2017. Modern EUV scanner is equipped with a high power EUV light source which can generate 13.5nm wavelength radiation at a high power up to 250W (above 400W light source is also under development), a full reflection mirror system in a

vacuum chamber which prevent high adsorption on EUV optical path and maximize reflectivity, as well as redesigned reflection mirror and reticle system with 0.33 NA from Zeiss SMT to enable up to 140 wph (Wafer Per Hour) throughput. Figure 2 shows visual structures of a deep UV immersion module TWINSCAN NXT:1980i and a latest TWINSCAN NXE-3400B EUV module which is clearly distinguishable from the deep UV module due to the light reflection system. With the help of EUV lithography system, together with economic affordable multi-patterning technologies semiconductor technology node can be pushed further to beyond 3nm, and extend Moore's Law to next decades (Figure 3). In the following chapter, main sub-modules of a EUV scanner will be briefly reviewed.

2. Light Source

Unlike the direct deep UV generation from excimer lasers, extreme UV light with 13.5nm wavelength can only be produced by excitation and

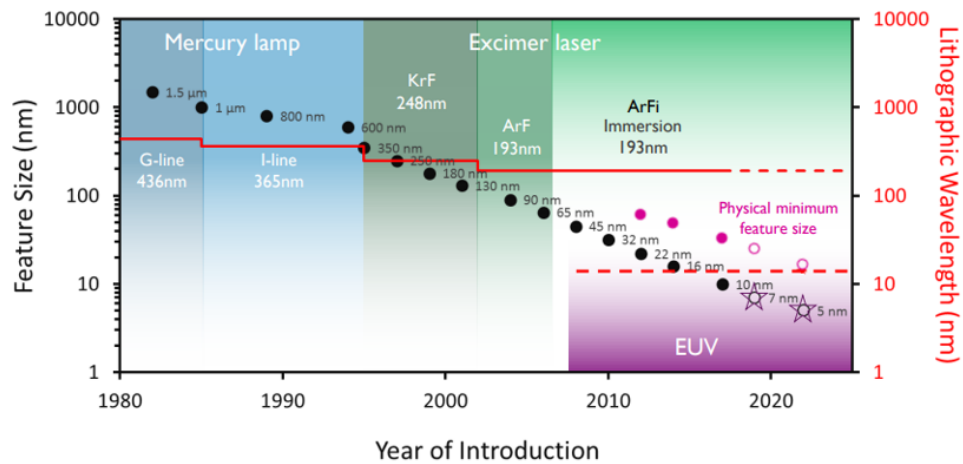


Figure 3. Evolution of patterning resolution and lithographic wavelength. Courtesy of Vu Luong, IMEC^[14].

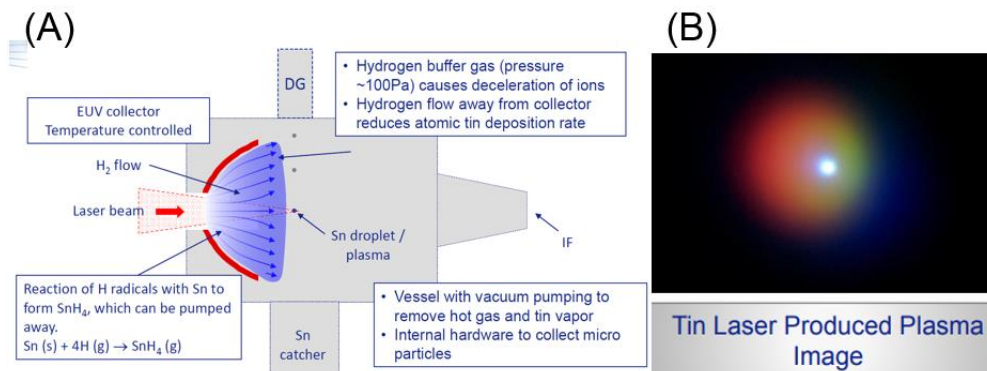


Figure 4. (A) Illustration of EUV light source vessel with hydrogen gas as buffer. (B) An image of laser produced plasma around a tin droplet^[21]. Courtesy of Igor Fomenkov, ASML.

relaxation of relatively inner electrons of atoms (e.g. Sn^{20+}), which could only be realized by atom ionization to form hot dense plasma^[15-17]. In a commercial ASML EUV system, high power CO_2 laser with 40~60kW has been applied to bombard liquid tin (Sn) droplet to generate dense plasma at high temperature around the droplet, where EUV radiation takes place^[18,19]. EUV photons are collected by a multilayer coated collector in an ellipsoidal shape (Figure 4A) and conducted to the reflection optics in a scanner. As a standalone component of ASML EUV scanner, the LPP (laser produced plasma) EUV light source is composed of high power laser generator, laser beam delivery system and EUV source vessel, which is one of the most distinguish parts of a EUV system compared with deep UV scanners^[15]. Due to the high gas absorption of 13.5nm wavelength UV light, the EUV vessel has to be kept in high vacuum which may suffer the system with particle contamination in contrast with deep UV chamber filled by clean nitrogen. In addition, high energy laser beam will

evaporate liquid tin and produce tiny microparticles of tin vapor. These tin deposit contamination in the vacuum chamber was one of the biggest challenges in EUV system^[20]. ASML is implementing hydrogen buffer gas with pressure about 100 Pa around the collector mirror to decelerate tin ions and reduce atomic tin deposition by a chemical reaction: $\text{Sn}(\text{s}) + 4\text{H}(\text{g}) \rightarrow \text{SnH}_4(\text{g})$, these SnH_4 gas product can be pumped away from the chamber, as shown in Figure 4^[21].

ASML subsidiary Cymer and Japan-based Company Gigaphoton are long-term rivals, both are struggling to win the battle to develop high power, high conversion efficiency light sources for EUV lithography applications^[22].

The following paragraph describe main parts of a typical LPP system in a market-available ASML NXE 3x00 EUV system.

2.1. CO_2 Laser Generator and Power Amplifier

High power of input CO_2 infrared laser is crucial to EUV final power output, which gives a

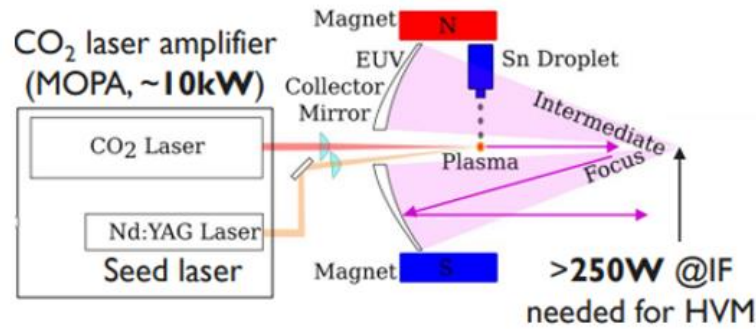


Figure 5. Illustration of EUV generator. Incident CO₂ and Nd:YAG laser beams hit tin droplet to generate dense plasma around the droplet, with the relaxation of plasma, EUV radiation takes place and focused by the collector mirror. Courtesy of Vu Luong, IMEC^[14].

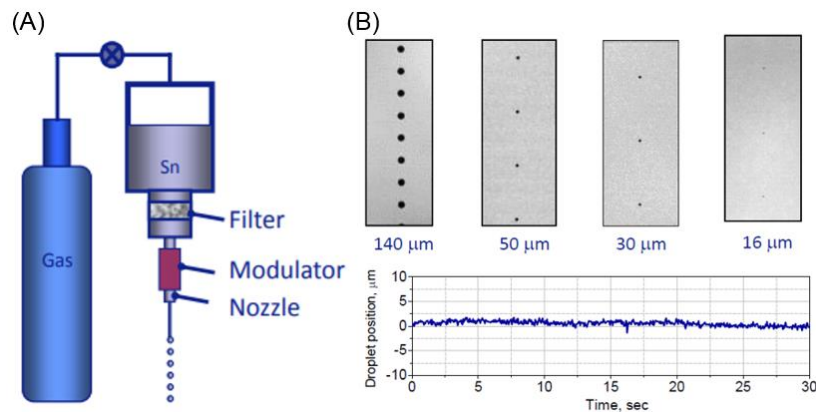


Figure 6. (A) Illustration of Sn droplet generator. (B) Snapshot of Sn droplets with different size and interval. Courtesy of Vu Luong, IMEC^[14].

second life of this mature laser technology^[18,19]. It was proven that tin plasma EUV could be driven by CO₂ laser pulse at 10.6 micron wavelength for the reasons of higher conversion efficiency, lower production of debris and higher average power levels without serious problems of beam distortions and nonlinear effects which occur normally in solid state lasers at high intensity. Practically a seed beam from Nd:YAG solid state laser at about 1 micron wavelength is preferred to be coupled together with the tin plasma as shown in Figure 4^[14]. An optimal timescale for an energy coupling was found to be a few nanoseconds for the Nd:YAG lasers and around ten nanoseconds for the CO₂ lasers.

The high power demand of a EUV source could be satisfied by a Master-Oscillator-Power-Amplifier system configuration. This new type of hybrid pulsed laser system combines pre-pulse seed laser, master oscillator, power amplifier (PA), fast flow systems, beam transport system and diffusion cooled planar waveguide lasers. The system can provide up to 40kW laser pulse, which could trigger 250W tin droplet EUV light source for latest ASML NXE

3400B EUV system with conversion efficiency (CE) up to 6%, so as to enable 140 wph (Wafer Per Hour) scanner throughput in HVM (High Volume Manufacturing)^[21]. New generation of 60kW modern is under development in labs.

2.2. Droplet Generator and Metrology

Inside the EUV source vessel, individual Sn droplets are continuously released with modulated size, speed and frequency from a nozzle of droplet generator (DG) located on top. As illustrated in Figure 5, tin raw material with high purity is melt in a container connected to the nozzle and pressed by an inert gas into the nozzle. Before spraying out of the nozzle, the tin jet is cut into droplets by mechanical vibration applied on in the nozzle under well-control. Separation space and size of droplets could be well-controlled by generator pressure and vibration frequency. Taking the nozzle outlet as a position reference, with the increasing distance from the outlet neighbor droplets coalesce together to from bigger droplets at larger separation space. The droplet size and timing must be precisely calculated

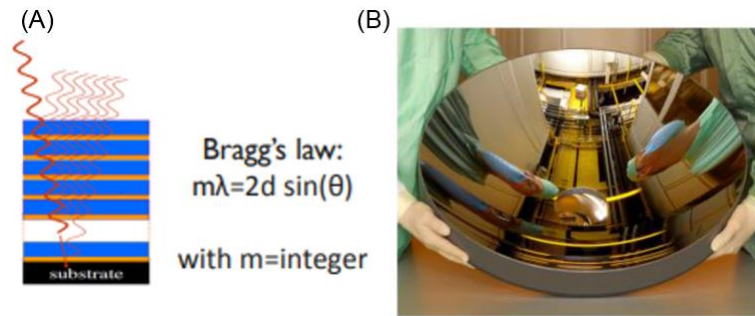


Figure 7. (A) Illustration of multilayer coated on collector mirror^[14]. (B) Photo of a real collector mirror from ASML^[21]. Courtesy of Igor Fomenkov from ASML and Vu Luong from IMEC.

and measured at the bombard position where laser pulse will hit the droplet to excite dense Sn^+ plasma. This angry-bird-like process play a critical role in EUV light source generation, and it has been found the EUV power is proportional to droplets speed and space between droplets. All components must be modulated with highest precision.

ASML third generation droplet generator produces with $27\mu\text{m}$ diameter of droplet with about 2700 hours average lifetime^[1].

2.3. Droplet Generator and Metrology

Plasma generated EUV light will be collected by an ellipsoidal MLM (Multi-Layer Mirror) collector with high reflectivity (Figure 7). The radius of the collector is well-designed to have its EUV focus on the vessel outlet called intermediate focus (IF) where EUV light is measured and conducted into the scanner vacuum chamber. In order to filter only 13.5nm EUV from the plasma halo and improve the reflective rate, collector surface is coated with multiple Mo/Si layers. By Bragg's law $n\lambda = 2d \sin(\theta)$, reflection wavelength λ could be precisely selected by adjusting layer thickness d and reflection angle θ . Main technical challenges include sputtering thickness and uniformity control of MLM layer, sputter target material purity, super fine polishing for surface roughness control, deposition of debris and contaminants, material decomposition and oxidation under EUV. The most advanced Bragg reflector of Mo/Si system can reach peak reflectance up to 70% (theoretically) of 13.5nm EUV light.

2.4. System Power Efficiency

EUV light source power is critical for high volume manufacture. To get an acceptable throughput of over 100 wph, EUV source above 200W @ IF (Intermediate Focus) is needed. Key factors for high source power are high input CO_2

laser power, high conversion efficiency (CE), high collection efficiency (reflectivity and lifetime) and advanced controls to minimize dose overhead, which follows below formula^[1,23]:

$$\text{EUV Power} = (\text{CO}_2 \text{ laser power} * \text{conversion efficiency [\%]} * \text{transmission}) * (1 - \text{dose overhead [\%]})$$

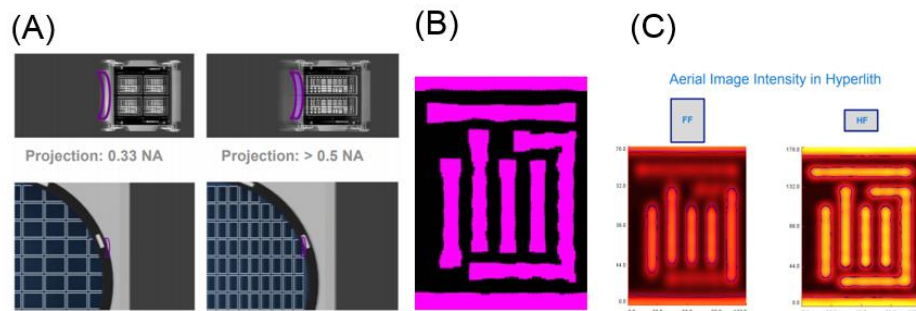
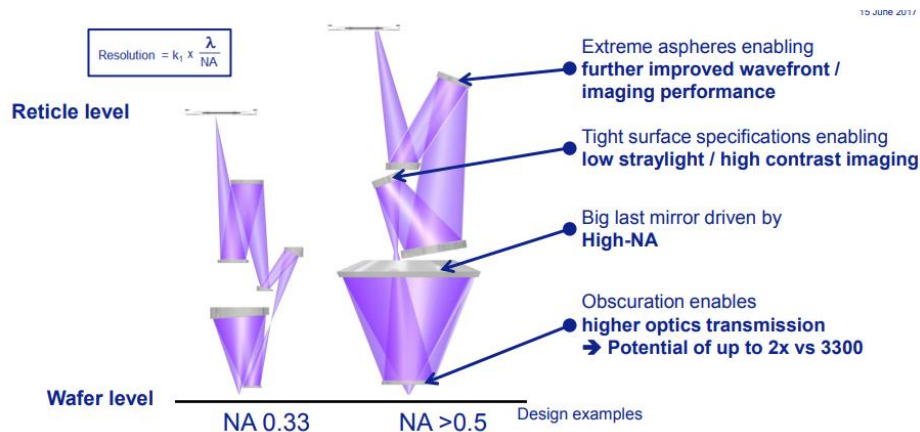
Latest ASML NXE3400B system adopts a 40kW CO_2 laser with system CE up to 6% and 10% dose overhead, which could generate 250W EUV light source. This enables wafer throughput up to 140 wph already acceptable for HVM. 400W EUV light source with 0.55 NA is under development at ASML, which will enable 185 wph throughput^[1].

3. Reflection System and High NA

Due to the strong absorption of 13.5nm EUV to any gases, the whole optical path must be fully reflective and enclosed in a vacuum environment, which is different from that of a deep UV scanner system. Moreover, in order to further reduce absorption and boost reflectivity, metal-based reflection mirrors is coated with alternating molybdenum and silicon (MoSi) layers with several nanometer in thickness (called Bragg mirrors), similar as the collector in EUV light source vessel. High reflectance is achieved with careful control of mirror quality, layer thicknesses, multilayer materials, interface quality, and surface termination. After several years of research and development, reflectance and film properties are relatively stable and can satisfy the requirements of an advanced EUV lithography system. The reproducibility of the reflectance peak was characterized to be as small as 0.2 percent^[24]. The coating uniformity has been improved to be better than 0.5 percent across a 150 mm diameter substrate^[25].



Figure 8. Internal structure of ASML NXE:3400B scanner. Source: ASML.

Figure 9. (A) Anamorphic half field (HF) exposure with high NA compared with full field (FF) with 0.33 NA. (C) shows aerial image intensity mapping between FF and HF A from a test mask feature (B), where HF presents much higher contrast^[28]. Courtesy of Jan van Schoot, ASML.Figure 10. EUV reflection comparison between NA=0.33 and high NA mirrors^[26]. Courtesy of Anthony Yen, ASML.

Reflection optics is also critical to next generation EUV scanner with high NA (> 0.5). High NA system will improve the wafer throughput to above 160 wph with dramatically reduced multi-pattern masks (number of LE), as shown in Figure 9. However, to reach high NA, reflection mirrors have to be redesigned to be asphere and the size of the mirror will be dramatically enlarged, accompany with EUV power over 400W^[26]. Besides, anamorphic half filed reticle and exposure system

has been introduced with 8x Y-magnification instead of traditional 4x magnification in both X and Y direction (Figure 9). Accordingly mask stage and wafer stage acceleration have to be adjusted to support twice number of scans/shots on wafer. Figure 10 illustrates mask comparison between 0.33 NA and 0.5 NA and wafer shot difference.

High NA EUV will benefit wafer throughput and reduce mask layers, but at a cost of super high EUV light power, very large mirror, asymmetry and

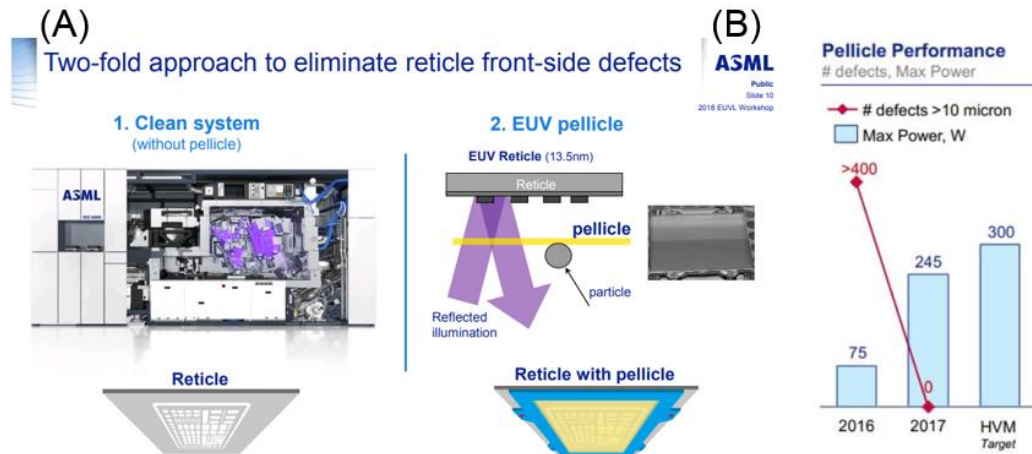


Figure 11. (A) An ASML presentation slide illustrates pellicle application on an EUV reticle and how particle can be isolated from reticle surface by a pellicle. (B) Defects decreased with the application of pellicle^[26]. Courtesy of Anthony Yen, ASML.

complicate reticle and wafer stage, as well as a special wafer cooling system. ASML future EXE module is supposed to be equipped with high NA optics^[26-28].

4. EUV Mask

In the EUVL reflective optical system, a reflective reticle is crucial to imaging quality and lithography process window on wafer. Similar as multiple coating on reflective mirrors in the vacuum system, 40 pairs of Si/Mo layers are deposited on the substrate of an EUV mask in order to get maximum reflection, which are capped by a thin film of Ruthenium (Ru) as thermal emission and reinforcing layer^[25,29]. On top of the thermal emission layer, absorber layers will be patterned to form “clear” or “dark” features. Material selection of absorber is critical to maximize absorption and minimize reflection. Shadowing effect and mask 3D effects are also related to absorber layer thickness and side-wall profile^[30]. Moreover, UV, thermal and mechanical stability of the reticle also need to be considered.

4.1. Pellicle Application

Usage of pellicle can prevent reticle from contamination and particles in the vacuum system, and greatly improve the lifetime of a reticle. But pellicle membranes on top of a reticle will reduce the EUV transmission and add extra cost to a reticle. ASML is struggling in both approaches: improve vacuum system cleanliness to avoid particle generation, and develop high performance pellicles membranes with high EUV transmission and low

defect^[26,28]. Progress has been made in recent years which makes the 1st generation pellicle ready for HVM which has been firmly tracked by Intel and other main EUV customers.

Advanced materials has been developed for pellicle membranes which should be durable under high power (> 300W) EUV radiation. SiN_x is found to be a good backbone rigid materials for mechanical stability, Ru-capped SiN and Graphene sheet have been investigated at ASML and IBM, Graphite film is being developed at Samsung, Carbon Nanotube (CNTs) thin film composite with SiN_x as a pellicle membrane has been developed and evaluated deeply at Hanyang University and IMEC. CNT enhanced SiN_x membrane was found to have 2.5 times decrease of deflection when pressure applied, without scarify EUV transmission^[31].

4.2. Mask Substrate and Bragg Mirror Layers

Physical properties of quartz glass based backbone influence aerial image deformation, and resist line edge roughness (LER) as well. Substrate macro properties like bow, material stress, surface roughness and flatness is determined by manufacturing process, e.g. lapping, cleaning, and fine CMP polishing. According to analysis from Applied Material, around 75% blank defects are introduced during manufacturing process of the substrate, compare to 25% of that from the deposition of multiple layers^[25]. On the other hand, heat transmission and high temperature mechanical stability of materials are also concerned. Applied Materials has taken a lot of efforts on reticle blank material investigation and development and already

Current EUV Mask Blank Structure

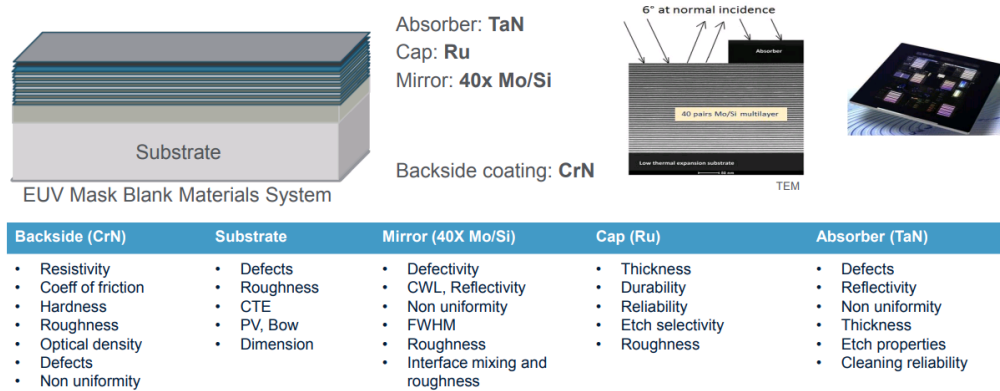


Figure 12. EUV reticle structure illustration from Applied Materials^[29]. Courtesy of Vibhu Jindal, Applied Materials.

made great progresses to improve substrate flatness, surface roughness, bow and defectivity to HVM level during last two years^[25,29].

Si/Mo switching Multilayers are sputtered on top of the substrate, which generate stress within multilayers and substrate interface as shown in Figure 12. One method is to selectively cut continuous mirror layer on uncritical area to release stress. Other critical properties which need to be preciously controlled are layer uniformity, thickness, interfacial roughness and defects within multilayers. It was observed that silicide formed within Si-Mo interface which could deteriorate EUV reflectivity, an optimized deposition process has been developed by Applied Materials to limit the silicide within sub-nm region, and such maximize reflectivity of EUV light^[32].

A capping layer on top of mirror layer is needed to enhance mechanical durability and reliability of the reticle, and improve the adhesion between mirror layers and the absorber. Ruthenium was implemented as a capping layer in state-of-the-art EUV reticles, other advanced materials or composites have been investigated as well within major plays like Applied Materials and Veeco^[33].

4.3. Absorber and Mask 3D Effect

Mask 3D effect in EUVL is more predominant for wafer image quality, compared with that in DUV lithography. Thickness of absorber and Chief-ray Angle (CRA) introduce asymmetry EUV reflection, mask shadowing and different printing behavior between horizontal and vertical features, as shown in Figure 13 where horizontal patterns A suffers much higher shadowing effect than vertical pattern B due to off-axis incidence angle only in Y direction. Mask

3D effect is also a result of multilayer mirror reflectance changes over incidence and wavefront or phase deformation of the material. In current EUV scanner modules, horizontal and vertical lines show different CD variation and contrast^[14].

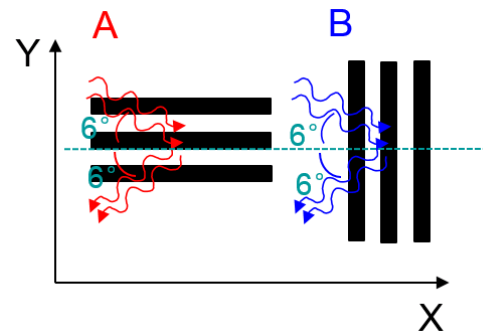


Figure 13. Feature orientation dependent mask 3D effect, horizontal features suffer more since they are perpendicular to the incident light plane.

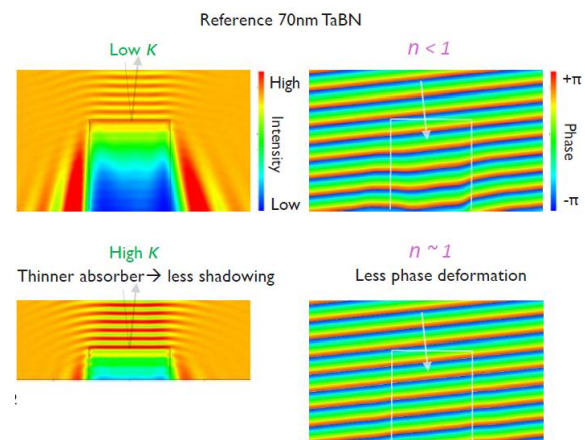


Figure 14. High k absorber can reduced mask 3D effect and get less phase deformation compared with low k absorber^[14]. Courtesy of Vu Luong, IMEC.

Ideal EUV absorber material should have a high extinction coefficient (k) and extremely low reflectivity, as well as small phase deformation after longtime EUV radiation at the same time, so that a reduced thickness and diminished 3D effect could be obtained. Boron doped TaN with about 70nm thickness is currently adopted for HVM EUV application with satisfactory results. But alternative absorber materials is also under evaluation. Today high- k absorbers such as Ni, Al, Co and their alloys have been evaluated by Veeco, IMEC^[34], ASML together with mask shops like Toppan and Hoya^[35], amorphous single phase materials as absorber is under development by Applied Materials^[29], which shows low surface roughness and stress, good chemical durability, good adhesion and etch selectivity with capping layer and less than 2% reflectivity for less than 45nm thickness. Pt-CrN Multilayer absorbers used for phase-shift mask (PSM) has been investigated by Hanyang University^[36]. On the other hand, EDA vendor Synopsys has evaluated absorber side-wall angle impact on optical parameters like NILS and intensity latitude by simulation^[30].

4.4. Actinic Inspection and Defect of An EUV Mask

Mask defect is one of the major challenges limiting the high volume manufacture of EUVL system. Since EUV light will penetrate into multilayer structure on the mask and reflected back, both internal and surface defects have to be taken into account of amplitude and phase shift of the reflected EUV light. Each component of a mask multilayer can contribute to final defect formation. As mentioned in previous paragraph, the quality of a mask substrate is decided by its bow, surface flatness and roughness. Impurities or surface roughness can generate dislocations and lattice boundary on the substrate surface which can be easily extended to upper layers of the reticle and eventually reticle surface. Uniformity of the multilayer Bragg mirror may suffer from pits or bumps buried within 80x multilayers during sputtering deposition due to any contamination inside the chamber, gas or target impurities, thickness also vary on tool variation, so as the absorber, capping layers and pellicles. Contrary to deep UV masks, the surface roughness of an EUV mask causes phase variations of the incoming wave fronts, which lead to intensity variations in the aerial image i.e. speckles which are local intensity inhomogeneities^[37,38]. Because of the

reflective nature and much smaller wavelength, the speckles contrast is significantly higher than that of the deep UV masks and may increase Line Width Roughness (LWR) at wafer level.

Fortunately not all defects or impurities in multilayers (ML) will result in disaster of reticle scrap, some substrate defects can be de-magnified when they spread onto the reticle surface through ML of the mirror^[39]. Some defects from multilayers can be locally repaired by E-beam similar as that for deep UV masks, as illustrated in Figure 15.

On the other hand, EUV mask characterization and actinic review of defects is also critical for HVM of EUVL since traditional SEM direct characterization cannot detect light phase changes and intensity variation due to mask internal defects or surface roughness. EUVL infrastructure consortium among ZEISS, SUNY Polytechnic Institute and SEMATECH has developed an actinic EUV mask Aerial Image Monitor System called AIMSTM EUV which is trying to close the gap^[37]. With the help of AIMS system, aerial image of the mask could be obtained before wafer exposure, any phase changes or surface roughness from will be captured and their impact on wafer and line edge roughness will be evaluated automatically.

5. EUV Photo Resist

Stochastic effect of photo resist is another major concern for EUVL application^[40-42]. Due to limited light source power, short wavelength and high photon energy of EUV light, Auger electrons or 2nd electrons will be generated after photon absorption by the resist, resulting in uncontrolled free electron path and photo acid spread after electronic relaxation, which is considered to be the main root cause of line edge roughness and CD variation^[43,44]. Interdisciplinary teams worldwide have been working on understanding fundamental mechanism of photo chemical reaction, new material development, and process control.

Gupta team from UCLA focus on LER analysis and impact on FEoL and BEoL of advanced FinFET technologies, LER mathematic model and LER impact on device reliability have been investigated^[45]. Resist half-pitch (HP) resolution, dose sensitivity and their relationship (Figure 16) to LER have been evaluated by Paul Scherrer Institut (PSI) to get a comprehensive solution^[46]. It was found that amount of photons, quencher and acid rank top three LER contributor, LER could be

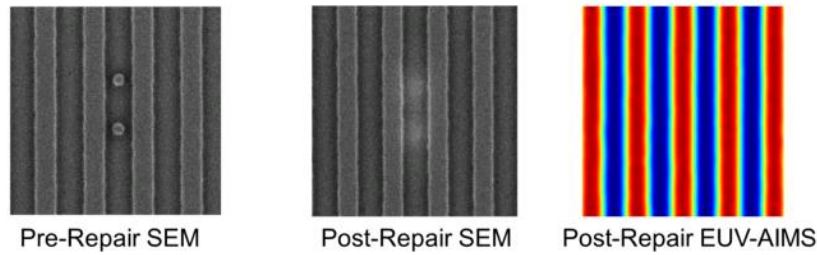


Figure 15. Defect on EUV mask could be repaired. From left to right, it shows two dot defects on line-space features, defects removed, and an aerial image after reparation^[37]. Courtesy of Dirk Hellweg, Zeiss SMT.

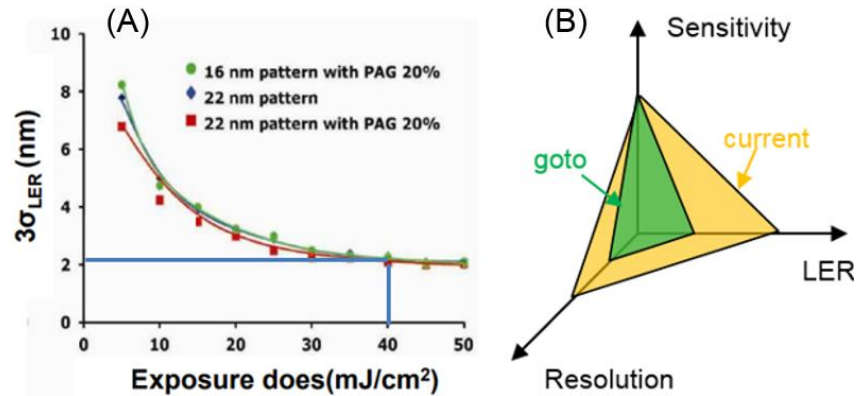


Figure 16. (A) LER is strongly dependent on exposure dose. (B) Resist sensitivity, resolution and line edge roughness (LER) are correlated each other, an optimization of smaller LER with good resolution and sensitivity is needed for EUVL.

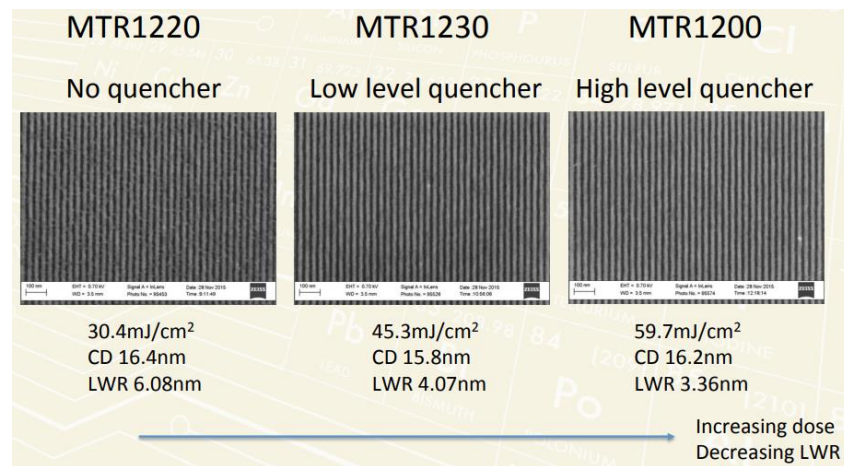


Figure 17. CDSEM images show LER is decreasing with increasing dose and resist quencher concentration^[48]. Courtesy of C. Popescu, University of Birmingham.

reduced by optimizing multi-trigger component ratio and quencher amount of the resist chemicals^[47,48].

Metal-contained photoresist, chemical amplified resists (CARs), photo acids (PAs) together with their backbone polymers have been investigated, material quantum yield and absorption coefficient have been measured and correlated to electron mean

free path within resist, providing a theoretical guide for photoresist selection. Resist chemical processes after EUV radiation are widely investigated by teams from Berkeley lab, Molecular Foundry, LBNL, Columbia Hill Technical Consulting and IBM Almaden Research Center^[49,50]. Numeric model of imaging mechanism for sol-gel prepared

organometallic polymer resists have been created by Inpria Corp., stochastic diffusion of secondary electrons has been simulated with changing dose^[51]. Innovative Inorganic-organic composite photoresist with a metal oxide core and polymer ligands has been synthesized as a non-CAR resist which is supposed to have smaller LWR ($3\sigma < 3\text{nm}$)^[52-54]. Moreover, lithography process control and optimization are also essential to LER reduction. Toshiro Itani and Takahiro Kozawa from Japan have conducted experiments to improve line edge roughness by alternating development, bake, rinse solution as well as resist top and bottom coating^[55].

Outgassing is another issue during resist exposure, hydrogen-contained molecules can contaminate the vacuum chamber, mirrors and reticles. ASML has developed a Dynamic Gas Lock (DGL) membrane to prevent outgassing spread and suppress DUV and IR during the wafer exposure^[1].

6. Summary and Outlook

In this paper, we had a broad but not specialized overview of extreme ultraviolet lithography technology and its application in mainstream semiconductor wafer manufacturing. Major EUVL modules include light source and vessel, reflection mirror system under vacuum, reflective reticle and aerial inspection system. Multilayer material fabrication and photoresist characterization are also critical in terms of EUV patterning performance, defectivity and edge roughness control. As EUVL scanner is an integrated system, final wafer printing quality is determined by every component especially the weakest ones. Thanks to worldwide collaboration and big investments in recent years, critical issues related to light source, substrate material and process, multilayer defects, mask absorber and defects, as well as resist edge roughness have been overcome in an ASML EUV scanner system, and wafer HVM using these EUV tools are already realized in those leading fabs worldwide.

Major progresses and challenges that are related to wafer throughput and pattern printing quality are summarized below.

EUV light source power

250W light power boosts wafer throughput to 140wph, which makes ASML EUV scanner ready for HVM. Next generation EUV source with further increased EUV energy power, improved conversion efficiency and better dose control is under development, not only to raise wafer throughput but

also to further minimize LER which is closely related to dose on wafer. It was found $40\text{mJ}/\text{cm}^2$ dose (compared with $20\text{mJ}/\text{cm}^2$ from current module) can dramatically reduce LER to smaller than 3nm. 400W EUV source will be implemented in next module of ASML NXE scanner soon. High power EUV is also critical to next generation high NA scanner.

Mirror and reticle defectivity

Impurities, thickness inhomogeneity of multilayer mirrors and reticles can change EUV light intensity or phase which will generate defects on wafer. Reticle surface roughness also contributes to LER. Besides superb quality fabrication of multilayer mirrors and reticles, the control of contamination and particles in vacuum chamber is also a big concern since there is no clean pressure gap protection in the reflection chamber and high energy nature of EUV. With the introduction of pellicles and DGL membrane, chamber defects have been reduced to a very low level. In order to detect not only surface impurities but also light phase changes due to internal defects, AIMS inspection system has been developed by ZEISS together with SEMATECH. This tool could check wafer aerial image and detect potential pattern failure on wafer.

LER and CD variation

Compared with deep UV lithography, line edge roughness is much worse for EUVL due to relatively low dose and secondary electron diffusion (stochastic effect). New photo resists such as metal-oxide with polymer ligands are being developed, lithography process flow has been optimized, and reticle flatness is well-controlled, all efforts have successfully reduced the LER to an acceptable level for an ASML EUV system. Further investigation is trying to reduce LER to below 3nm for 3σ from current 3.5nm range from inorganic resist and 5nm range from CAR.

Mask 3D effect

Due to absorber thickness and the chief-ray angle of incident EUV light onto the mask, horizontal and vertical features show different imaging behavior and critical dimension change on wafer, this is called shadowing effect. Mask 3D is also related to reticle blank flatness and bow, multilayer EUV reflectivity, and absorber properties. These effects will decrease the margin of process window with a reduced or shifted depth of focus (DOF). By introducing phase control SMO and OPC

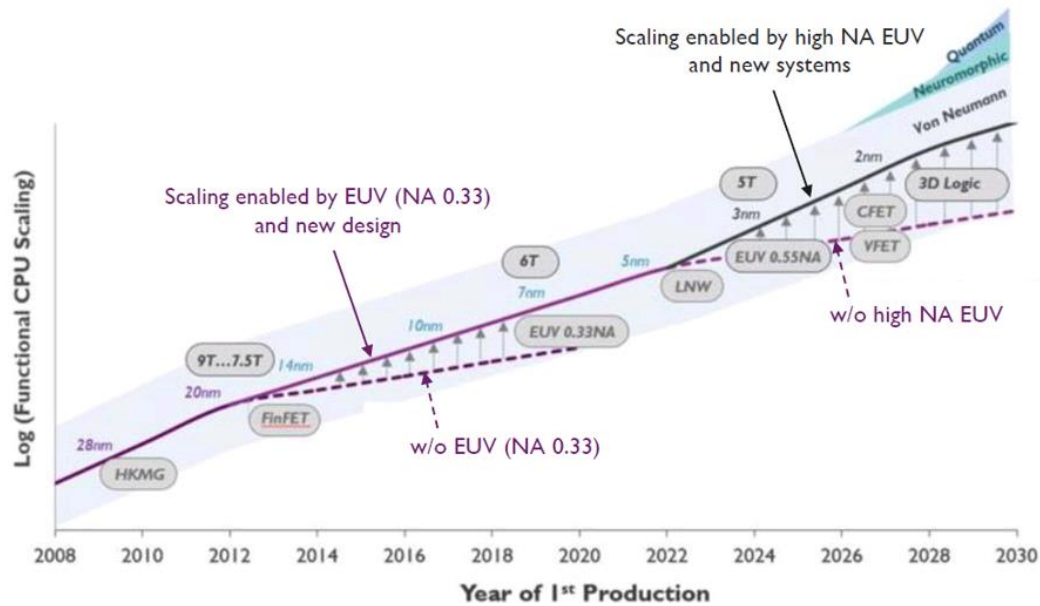


Figure 18. Technology node scaling is driven by the development of lithography and DTCO. High NA EUV will lead the industry in next decade^[14]. Courtesy of Vu Luong, IMEC.

correction, orientation-dependent mask CD bias could be compensated. High-k absorbers are also under development to help further reduce shadowing effect. In next generation of high-NA EUV scanner, anamorphic half field reticle will be introduced to overcome x-y asymmetry and improve throughput^[56], but with the cost of design, OPC and mask complexity.

EUVL has achieved great progress since 2015, most of breakthroughs take place after the formation of EUV industry alliances among big player like ASML, INTEL, TSMC and SUMSANG. Industry requirements combined with strong financial support finally drive this technology into HVM. As the only EUVL scanner commercial provider, ASML is going to sell over 30 EUV modules in 2019. The market is ramping up and this revolutionary technology will lead the industry to the next decade^[57] (Figure 18).

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