Review Article

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Development and performance of EUV pellicles

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Abstract: In a lithography process, an image on a mask (reticle) is projected onto a wafer. Continuous decrease in feature sizes also led to a reduction in the wavelength used for exposing. The next step is the move from 193-nm light to extreme ultra-violet (EUV) at 13.5 nm. This poses a lot of challenges that have been overcome in the past years. One of these challenges is the protection of the reticle from front side defects. This protection can be achieved by the use of an EUV pellicle. This is a thin membrane that protects particles from landing on the reticle surface, as will be explained in more detail later. With multiple semiconductor manufacturers preparing for volume EUV manufacturing, the need for a volume production-ready pellicle solution is here today. This article gives an overview of the performance of the current EUV pellicle solution and the status of the development of future EUV pellicles.

Keywords: EUV; lithography; mask defectivity; pellicle; reticle; thin membrane.

1 Introduction

In order to introduce EUV to volume production, several challenges must be solved [1, 2]. Mask frontside defectivity is one of them, which is the focus of this paper.

A pellicle is a thin membrane that protects a projection reticle from contamination. It is mounted after mask fabrication, and it protects the reticle during all phases: transport from mask shop to FAB, stocking, entering the scanner into vacuum, being handled in the scanner over various stages, and being exposed. The cycle within the FAB repeats a number of times before the reticle is sent back to the mask shop for cleaning. The basic working principle of the EUV pellicle is the fact that particles will land on the pellicle membrane (which is not in focus) instead of on the reticle (which is in a field plane, so any obscuration will print directly onto the wafer; see Figure 1 for the basic working principle).

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2 Challenges

The basic challenge of manufacturing a EUV pellicle is the fact that solid materials are mostly opaque to EUV light; this requires an EUV pellicle to be extremely thin. Typical thickness of the current pellicles is approximately 50 nm, leading already to typical EUV transmission losses of about 10% single pass. The film will absorb some of the incoming and outgoing light, leading to elevated temperatures in the film. Consequently, the pellicle is prone to degradation, as a small change in material thickness or composition due to this heating can change the mechanical, physical, chemical, and optical properties of the membrane.

The film will absorb some of the incoming and outgoing light, leading to elevated temperatures of the film. At higher EUV source powers, pellicle films reach temperatures in excess of several hundred degrees C. These temperatures can lead to a reduced lifetime or failure (by pellicle film material structural changes, melting, layer diffusion, etc.) See Figure 2 for an overview of the challenges of pellicle film development.

The current pellicles, as made by ASML, have a power capability of at least 125 W, with a next-generation under development for higher source powers [3].

Although small particles on the film do not print, the film still needs to be free of larger particles that can be up to several micrometers in size.

Mechanically, the pellicle membrane also has to survive the transition in and out of the vacuum environment of the EUV scanner. While doing so, the pellicle may not deflect more than the mechanical clearance it has in the pod that is used to load it into the scanner. The amount of differential pressure in the load lock depends on a set of parameters: load lock vent speed (throughput), the restriction of the gas going in and out of the pellicle

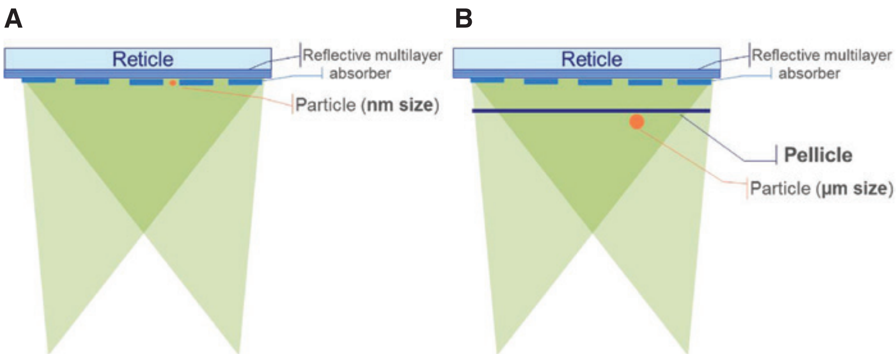


Figure 1: Incident and reflected light from a reflective EUV reticle (A, left) without a pellicle; nanometer-sized particles might print at wafer level, and (B, right) with a pellicle (double light pass); particles are kept out of focus reducing printability.

volume (the space between the mask and the pellicle), and the maximum allowable pressure differential to keep the pellicle within the deflection limits.

The ASML pellicle, has a small slit (≈0.2 mm) between the reticle and the pellicle frame; this has two main features: the only point of contact between the pellicle and the reticle are at the four stud mounts, therefore, limiting pellicle-induced reticle deformations, as the actual pellicle frame is suspended above the reticle (see Figure 3 for a cross section). Second, the slit can act as a pressure equalizer, while still suppressing particles from entering the inner pellicle volume. Feasibility tests showed that this suppression is effective [4]. Also, the low resistivity of an open gap relative to the filters allows a high load lock throughput. Mitsui Chemicals [5] showed a novel closed pellicle design based on filters. Although removability and compatibility with the pellicle tooling was not addressed in this study, it shows that in the future, filtered EUV pellicle designs might become a reality.

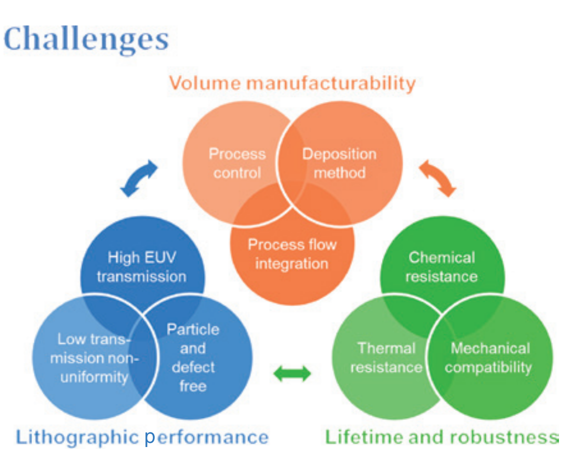


Figure 2: Challenges for pellicle manufacturing.

3 ASML pellicle membrane development

ASML developed a membrane for release toward volume EUV customers. This generation pellicle membrane is a capped polysilicon membrane that contains an emissive layer to improve heatload capability. In 2016, this membrane was taken from prototype manufacturing to volume. The initial development also included sizing: after first proving the capabilities on smaller samples, over time the film size was increased. See Figure 4 for an overview of the sizing steps. Pellicles are shipped to several EUV customers where they are used in EUV scanners. ASML also is continuously exposing pellicles on scanners for performance and lifetime testing (see later section on pellicle performance).

ASML's next pellicle generation, also based on a polysilicon core, will show improved heatload capability, lifetime, and uniformity.

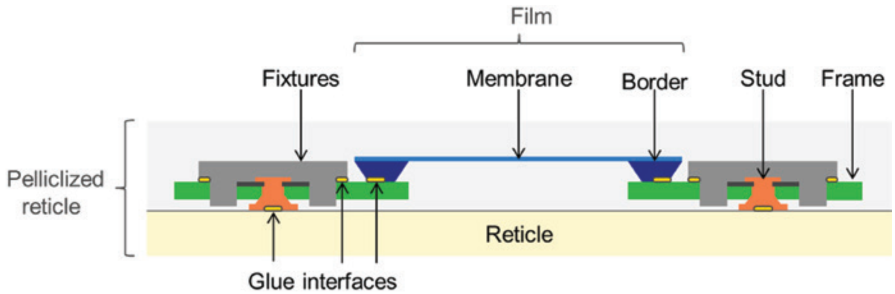
4 ASML: NXE pellicle

The NXE pellicle is a removable design, where the pellicle assembly can be removed for intermediate reticle inspection.

The concept of the NXE pellicle is shown in Figure 3; the red studs are the only interface of the pellicle to the reticle. These are glued to the reticle. The pellicle frame and membrane are then mounted on these studs.

The NXE pellicle concept can be viewed as a three-step operation, with each operation having a dedicated supporting tool:

1. Stud fixation. The attachment of the pellicle will be done by the gluing of the four studs to the reticle frontside. This attachment of studs to the reticle frontside



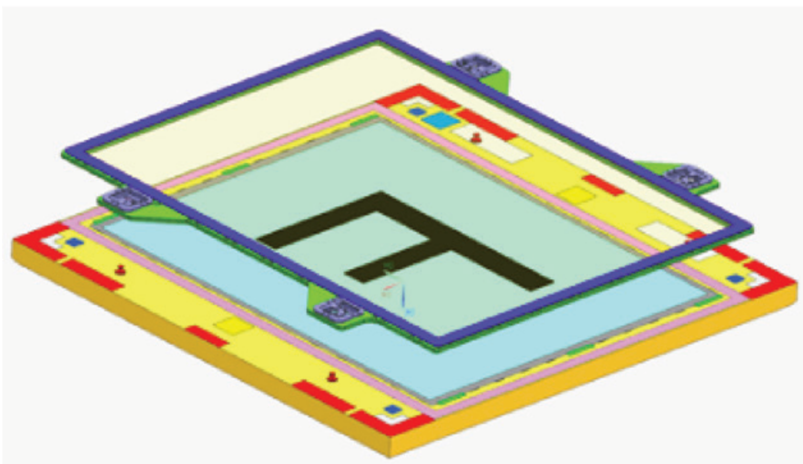


Figure 3: The NXE pellicle concept.

is accomplished with a tool called SFT (stud fixation tool). The four studs are the only mechanical interface to the reticle.

2. Pellicle mounting and demounting. A second tool, the MDR (mount demount remount) tool, will cleanly attach or detach a pellicle onto a reticle equipped with studs. The pellicle interfaces to the studs with four internally elastically decoupled fixtures, attaching to the studs by spring load. The decoupling springs ensure that the impact of the pellicle on the overlay is minimized. To allow the inner gas pressure of the pellicle to equalize to the outside, the pellicle is mounted at an offset from the reticle front surface. Tests were conducted to validate the defectivity performance of this concept. No particle transport through the small gap was observed.
3. Stud removal. It is anticipated that studs will be removed from the reticle during some points in the life of the reticle. Stud removal is accomplished by a third tool, the SRT (stud removal tool). The SRT will remove the stud by elevated temperature, releasing the stud from the reticle.

The NXE pellicle is a solution that can be used with the ASML film or, alternatively, with future films that are under development at ASML and other parties.

Because some pellicle film materials are nontransparent to DUV inspection wavelengths, inspection of a reticle with such a pellicle is only possible at actinic wavelengths. The NXE pellicle allows pellicle removal for intermediate reticle inspections so inspection can be done with the current 193-nm patterned mask inspection tools.

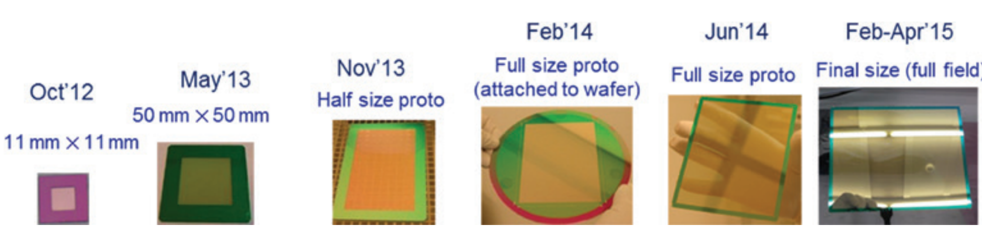


Figure 4: Overview of the sizing over time.

4.1 Pellicle performance

NXE pellicles have been in a continuous test plan at ASML. A summary of the achievements, so far, is given below.

4.1.1 Defectivity

ASML tested the defectivity performance of the NXE pellicle concept in a series of tests; also, at customer sites, tests are ongoing [6].

In the figure below can be seen how the tests are executed at ASML.

After 7000 cumulative wafers exposed, no reticle frontside adders (>68 nm) were observed. See Figure 5 for an overview of the test sequence that was conducted. Testing will continue at ASML to get more defectivity performance data.

4.1.2 Imaging

ASML showed the results of imaging tests with pellicles in [3, 7, 8]; the work shows that transmission uniformity is the major contributor to pellicle-induced imaging effects. Stray light due to reflection on a pellicle is another contributor. DUV reflectivity can be eliminated by adding a filter membrane in the optical column [9] and Figure 6. The image was acquired with a pellicle and with and without a filter membrane; no reticle error correction (REC) was used.

The figure below shows the imaging impact of the use of a pellicle as was reported earlier [3].

4.1.3 Overlay

A test was conducted where the overlay fingerprint of a bare reticle was compared to the situation with glued studs and an installed pellicle. With the preliminary tooling available at that time, the maximum observed overlay effect of the pellicle using preliminary tooling was measured to be 0.17 nm [3] (see Figures 7 and 8 for the result). After the final mount/demount tools are operational, overlay tests will be repeated.

A test was also conducted where a repeated pellicle placement was done on a reticle. This test showed that the replacement of the pellicle on the reticle did not result in measurable overlay effects (<60 pm) (see Refs. [3] and [4] and Figure 9 for more details).

4.1.4 Lifetime (monitoring)

ASML is continuously using pellicles in scanners for lifetime testing with intermittent offline pellicle measurements. The removable design of the pellicle enables the

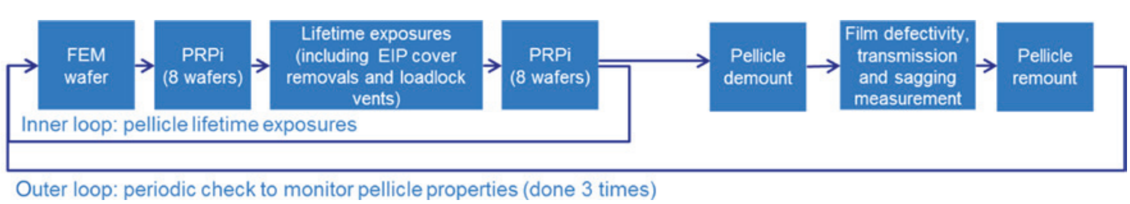


Figure 5: Defectivity test run with light.

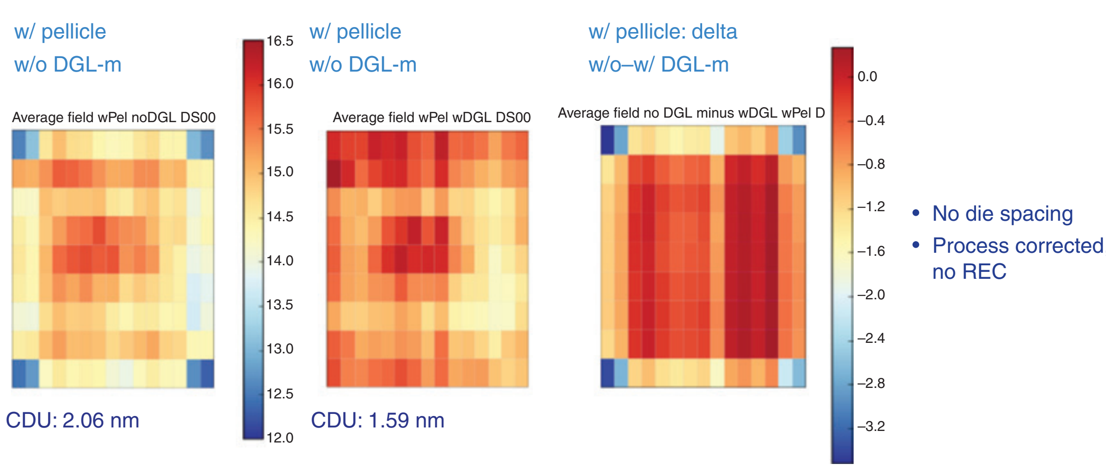


Figure 6: Mitigation of (DUV) reflectivity by additional filter (DGL-m).

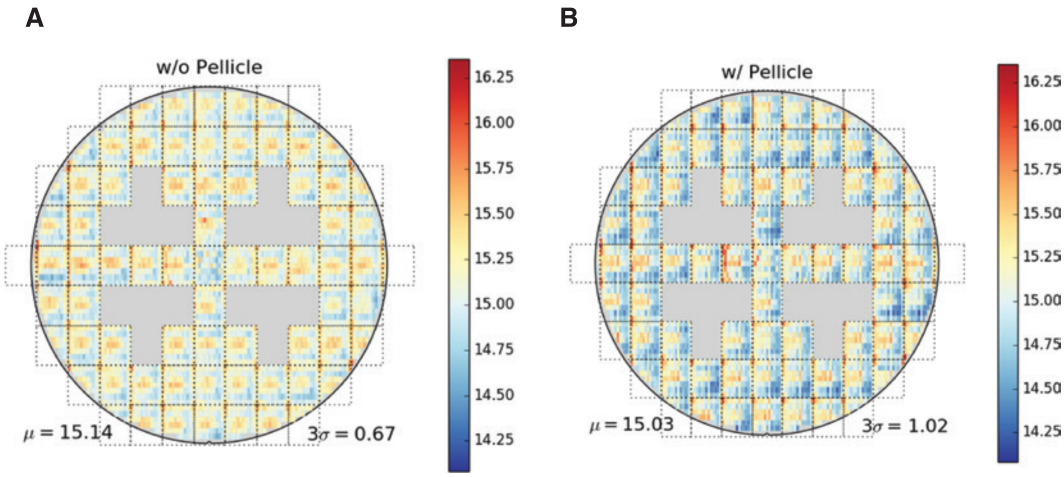


Figure 7: (A) Left: pre-fingerprint exposure without a pellicle; (B) right: same exposures after mounting a pellicle on the reticle (units: nm; μ, average CD).

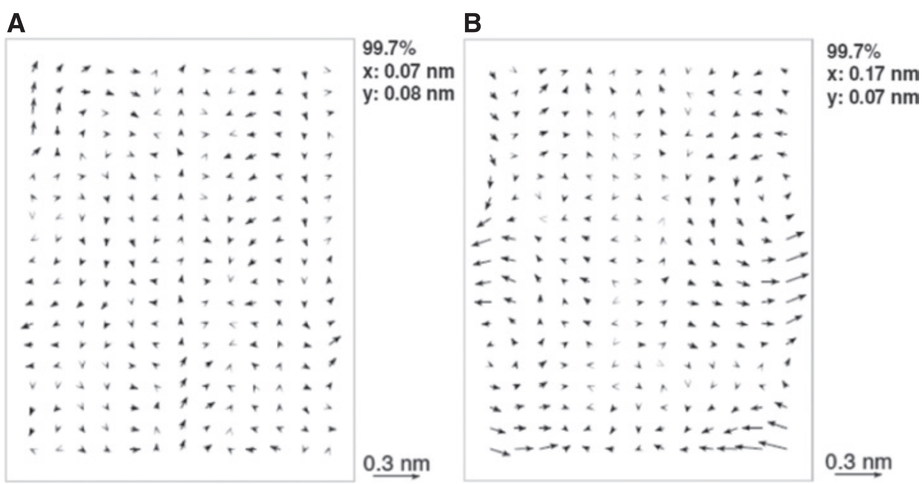


Figure 8: (A) Left: overlay effect of the gluing of the studs on a reticle; (B) right: overlay effect of the NXE pellicle.

pellicle to be taken off the reticle periodically. The pellicle is then measured on EUV transmission (-uniformity), deflection under pressure, and defectivity. Investigations are ongoing to link property changes in the pellicle to lifetime. The target lifetime for production pellicles is the exposure of 10,000 wafers.

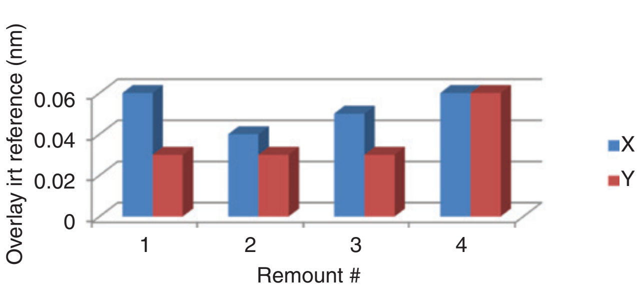


Figure 9: Overlay δ plot pellicle remount measurement (reticle with a pellicle).

5 Overview of current EUV pellicle developments

In this chapter, a limited summary of the work that is internationally done on pellicles is listed. The overview is, by no means, intended to be complete.

5.1 Intel – Shin Etsu

EUV pellicle publications started about 10 years ago with Intel [10, 11] and Shin Etsu [12] reporting on in EUV scanner experimental tests with gridded pellicles. In these studies, gridded pellicles with varying standoffs and densities were imaged. ASML [13] reported later on a theoretical study on the imaging effects of gridded pellicles. The basic conclusion of this study was that grids that actually give a significant mechanical benefit are not suitable for the imaging use cases in the scanner. For this reason, ASML is focusing on free-standing pellicles since 2013.

ASML started EUV pellicle feasibility work on multi-lattice-type free-standing membranes developed by Phystex/IPM [14]. The early prototype frame hardware and support was courtesy provided by Intel. Subsequently, ASML used polycrystalline silicon as a base material, capped with silicon nitride. These films can be manufactured with a process that yields an inherited prestress in the film material. This prestress limits the deflection that occurs when the film is subjected to a differential pressure, for example, when exposing or when transitioning in and out of vacuum. This characteristic proved to be an essential component in the size scaling that was done at the time. See below for an overview over time of how the pellicle size increased [15].

Manufacturing and co-development of these films was done by Philips Innovation Services and Philips Research. After successful preproduction, a volume supplier was engaged for volume production.

5.2 ASML research

For the power roadmap beyond 250 W, ASML research is looking at alternative pellicle materials.

The ideal requirements of the pellicle are maximum EUV transmission ideally above 90% single pass, chemical stability, and thermo-mechanical resistance under EUV/H2. As fulfilling all the requirements in one single layer is a challenge, different layer film architectures are looked at. ASML research investigates such architectures, both silicon- and carbon-based. The base materials are complemented by nanometer-thin coatings that increase IR absorption and, thus, enhance emissivity and that prevents oxidation of the base material occurring in high-power EUV systems (see Ref. [16] for more information).

5.3 IMEC developments

At IMEC, a pellicle program is ongoing, active in several fields. Apart from looking at industry compatibility with the EUV pellicle infrastructure, fundamental research is also ongoing.

Carbon-based materials: research is done on next-generation pellicle materials, for example, carbon nanotubes (CNT). The challenge with all carbon-based materials is to have chemical resistance to the H_2 plasma environment while exposing. IMEC showed progress in capping CNT materials, showing results on PVD and ALD-deposited capping layers.

Also, silicon nitride DSA-assisted manufactured structured pellicles are researched [17]. With these, additional transmission can be achieved due to the open nature of the material.

5.4 IBM developments

At SPIE Advanced Lithography 2016, IBM [18] showed a method of measuring the emissivity of pellicle membranes. Also, the dynamic heating conditions under exposure are explained.

Temperatures (expected for SiN pellicles) shown in this paper are higher than the operating temperatures measured with the coated pellicles made by ASML, which show an emissivity of approximately 0.3–0.45. Under thermal load, membrane materials will expand. In this paper, an analysis was made on the wrinkling due to the expansion.

IBM also showed progress on the fabrication of a full-size silicon nitride pellicle in 2015 (see Ref. [19]). Although high EUV transmission levels have been achieved, the heatload capability of uncapped silicon nitride has yet to improve to be a viable solution for high-volume EUV manufacturing.

Another topic of work is the inspection of defects on patterned masks with mounted EUV pellicles using DUV inspection systems. IBM reported both on the work on a 193-nm transmissive film as on experiments to measure patterned masks through a pellicle [20]. Although the experiment to inspect a mask succeeded, there was an impact on measurement time. The pellicle used was a 20-nm silicon nitride film.

5.5 Samsung developments

At IEUVL 2015, Samsung showed a study on the critical temperature for Si-based pellicles. This work shows the need for measures reducing the temperature of silicon-based pellicles as silicon transitions can occur above a certain threshold temperature. (Adding an emissive layer

[21] can keep the film temperatures below the critical temperature up to higher source powers.) The presentation also shows the results of heatload tests, showing that c-Si is thermally more stable than p-Si. Boron-type capping layers, instead of silicon nitride, are proposed for better thermal stability. Finally, carbon-type pellicles are proposed as the next-generation pellicles. These are proposed for better mechanical strength (thus, thinner, more transmission) and better heatload capability.

5.6 Hanyang University developments

At Hanyang University, South Korea, pellicle developments are ongoing. Some of the ongoing research includes:
- SiN (silicon nitride) pellicle manufacturing by LPCVD process
- Imaging impact simulations
- Carbon-based (graphene) pellicles
- Studies on the mechanical properties and behavior of thin (pellicle) membranes
- Modeling and simulations of thermal load on thin pellicle membranes.

Overall, the work internationally done focuses mainly on the following roadmap items:
- Increase in transmission (throughput improvements) and improve transmission non-uniformity
- Higher EUV power capability and lower thermal stress
- New materials to increase chemical resistance
- Compatibility (e.g. inspection, reticle cleaning)

6 Conclusions

As reported in this paper, a lot of progress has been made by several groups. Work on carbon-based pellicles, which can enable EUV transmission values of over 90% single pass, is ongoing at various aforementioned locations. The current ASML NXE pellicle is on track to meet the industry's requirements to go into volume production. Work is also progressing on the infrastructure being, for example, inspection methods, reticle cleaning, and mask shop tool for pellicle handling. Research on future pellicle membranes for higher-power nodes also shows progress.

Currently, ASML is supplying pellicles to multiple customers, which expose wafers with pellicles in their own scanners. Also, ASML is executing a multitude of tests, in particular on lifetime and defectivity on its own scanners in the factory.

The current ASML pellicles are capable of handling 125 W EUV source power; the next generation will have an improved power capability.

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