Carbon nanotube pellicles: imaging results of the first full-field extreme ultraviolet exposures

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Abstract. Extreme ultraviolet (EUV) lithography was recently implemented in high-volume wafer production. Consequently, maximizing yield is gaining importance. One key component to achieving optimal yield is using a pellicle to hold particles out of the focal plane and thereby minimizing the printing of defects. The carbon nanotube (CNT) pellicle is a membrane consisting of a network of CNTs with a demonstrated EUV transmission (EUV-T) of up to 98%. The challenge is balancing the CNT material parameters for optimal performance in the EUV scanner: low probability for particles to pass, low impact on imaging through scattered light, and high durability in the scanner environment, while maintaining high transmission. We report results of the first full-field CNT pellicle exposures on an EUV scanner. We demonstrate handling of the pellicles, without breakage, and provide a first assessment of their imaging behavior. Multiple single- and double-walled uncoated CNT pellicles with EUV-T of up to 97.7% were exposed on the EUV scanner at imec, and minimal impact on the imaging was confirmed. In these exposures, uncoated CNT pellicles that do not yet meet the specifications regarding lifetime were used. Therefore, ongoing developments focus on CNT durability in scanner environments. The presented demonstration proves the value of a CNT-based EUV pellicle solution. [DOI: 10.1117/1.JMM.20.2.021005]

Keywords: pellicle; carbon nanotubes; mask defects; extreme ultraviolet lithography; ASML NXE:3400.

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1 Introduction

1.1 *Carbon Nanotubes for EUV Pellicles*

Particles that fall on the patterned surface of a photomask can create repeating defects in every printed wafer field. In deep ultraviolet (DUV) lithography, the use of a pellicle is a common practice for removing the risk of fallen particles. The pellicle is a transparent membrane mounted a few millimeters above the surface of the mask to hold particles out of the mask's focal plane. For 193-nm wavelength lithography, the pellicle is very thin and transmits over 99% of the light, which ensures that the imaging impact is minimized.[1–3] For extreme ultraviolet (EUV) lithography, the introduction of pellicles is much more difficult. Few materials have the potential of high EUV transmission (EUV-T) beyond 90%, and even fewer materials are at the same time compatible with EUV powers beyond 600 W. In addition, the pellicle needs to be strong to be suspended over a large area of the mask (∼110 mm × 140 mm). A full-size, highly transparent membrane that can survive exposures at the higher power levels associated with high volume has yet to be identified.

Earlier imec publications have described the development and testing of carbon nanotubes (CNTs) for the EUV pellicle application.[4,5] CNTs are sheets of graphene rolled into seamless

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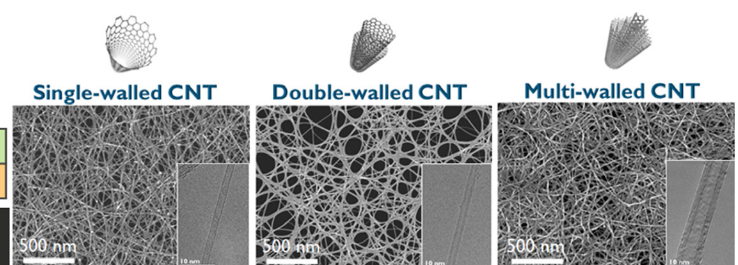
cylinders. In contrast to the continuous membranes based on polysilicon,[6,7] a CNT membrane consists of a network of overlapping nanotubes. CNTs are available in different basic tube configurations, i.e., single-walled CNT (SW-CNT) made of a single graphene layer and double-walled (DW-CNT) or multi-walled CNT composed of several concentric cylindrical graphene shells. Although the concept of using CNTs for the EUV pellicle is very promising, there are still optimization items for future scanner use.

1.2 *CNT Pellicle Development Status*

CNT membranes are extremely configurable. This design flexibility is both a blessing and a burden. At this point, we have developed a good understanding of the tunability of CNT parameters to modify membrane transmission, scattering, emissivity, and strength. The scorecard table in Fig. 1 provides a general assessment of the different types of CNT membranes.

When light passes through the pellicle, it can be scattered by the nanostructure and lead to unwanted CD variations. Scattering measurements and simulations have been treated in separate publications.[8,9] Non-actinic (DUV) through-pellicle reticle inspection has been confirmed.[10] Finally, the ability to survive in the H-plasma environment for extended periods of time in the EUV scanner remains a development item. We have studied some of the lifetime limiters, and our current efforts are focused on lifetimes under 600-W scanner conditions.[8,11] A coating is expected to improve lifetime properties of the CNT membrane, but it must be optimized for characteristics such as transmission and scatter.[9,11]

This paper reports the results of the first full-field CNT pellicle exposures on an NXE EUV scanner. It demonstrates handling of the pellicles on the scanner, without breakage, and provides a first assessment of their imaging behavior. Multiple single- and double-walled uncoated CNT pellicles with EUV-T of up to 97.7% were selected and exposed on the NXE scanner at imec. In the following section, we describe our exposures and present measurement results for the impact of the pellicles on dose-to-size, intra-field uniformity, and flare. The outcome of these tests confirms minimal impact on the imaging.



Exceeds target
Fails to meet target

Uncoated CNT pellicle

Membrane property	Target	SW-CNT	DW-CNT	MW-CNT
EUV Trans. (mean)	>90%	98%	97%	95%
EUV Trans. (3σ unif)	<0.4%	0.2%	0.3%	0.3%
EUV scattering	<0.3% (tbd)	0.12%	0.14%	0.25%
EUV scanner lifetime	>600W w/plasma	Survived 30 min 600W with membrane degrade		
Through-pellicle, non-actinic metrology	achievable	Optical demonstrated, SEM feasibility	Optical demonstrated	Anticipated by extension

Note: values are the best results routinely achieved on 1 cm² development samples

95% EUV-T
98% EUV-T
97% EUV-T

3 single-walled (SW) & 2 double-walled (DW) uncoated CNT-pellicles were selected for NXE:3300 exposure at imec

Fig. 1 CNT pellicle scorecard, summarizing target and achievements for key CNT pellicle metrics.

2 Full-Field CNT Pellicle Exposure Results

2.1 *Experimental Setup*

Five full-field CNT pellicles were mounted on pellicle frames and used in combination with two different EUV reticles. Of these five pellicles, two were double-walled (referred to as DW-1 and DW-2) and three were single-walled (referred to as SW-1, SW-2, and SW-3). The DW pellicle set on the one hand, and the SW pellicle set on the other hand, were both created with their respective processes. The only intentional variation within each set was a modification to change the membrane density (impacting transmission). It should be noted that all CNT pellicles were uncoated. The two reticles are referred to as SLBF and ATP. The SLBF mask is dominantly a bright field mask, which we used for flare tests and for sub-E_0 exposures and measurements on ASML YS250. The ATP mask is a test mask with many repetitions of a 32-nm pitch (P32) L/S CD-SEM module. As depicted in Fig. 2, the SLBF mask has been exposed using CNT pellicles DW-1, SW-1, and SW-3, with measured EUV-T of 96.9%, 97.7%, and 95.3%, respectively. The difference between SW-1 and SW-3 is in their density. The pellicle film of SW-3 is denser, and therefore it has slightly lower transmission. The ATP mask was exposed using CNT pellicles DW-2 and SW-2. Also, reference exposures without any pellicle were performed with both masks. Due to the logistics of reticle shipping for demounting and mounting pellicles, the time between subsequent exposure sessions with different pellicles was typically 7 to 10 days.

Exposures were done on the ASML NXE:3300B at imec, interfaced with a Lithius Pro track from TEL. The resist stack on the wafers consisted of a CAR resist on a 20-nm underlayer. The sub-E_0 exposures of the SLBF mask used 40-nm resist thickness, with a conventional illumination source shape at σ0.879. The P32 L/S exposures of the ATP mask used a 30-nm resist thickness, with a standard dipole 90Y illumination source shape at σ0.868 to 0.349. Although the P32 is well resolved using this exposure condition, the illumination condition is not optimized for high contrast or low roughness. Rather, we chose the standard dipole condition to increase the sensitivity of the L/S pattern to exposures dose variation. The NXE scanner was not equipped with a DGL-membrane (Dynamic Gas Lock). Since out-of-band scattering from these CNT pellicles is very low, a DGL-membrane is not required for this purpose.

The choice of uncoated pellicles for our scanner exposures is based on our goal to demonstrate handling and imaging of full-field CNT-pellicles. The chosen pellicles will not yet meet lifetime targets in the current scanner conditions. Ongoing development focuses strongly on extending CNT pellicle durability in the scanner environment.[11]

2.2 *Impact of CNT Pellicles on the Dose-to-Size*

A pellicle absorbs some amount of EUV light, both during the first pass when the light is incoming to the photomask and the second pass after reflection from the mask. Therefore, the addition

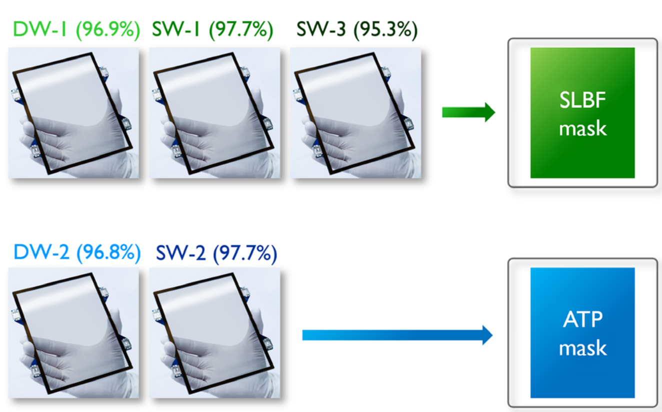


Fig. 2 Five different full-field uncoated CNT pellicles were mounted on two different masks. Two pellicles are double-walled (DW), and three pellicles are single-walled (SW). The measured EUV-T values are given between brackets.

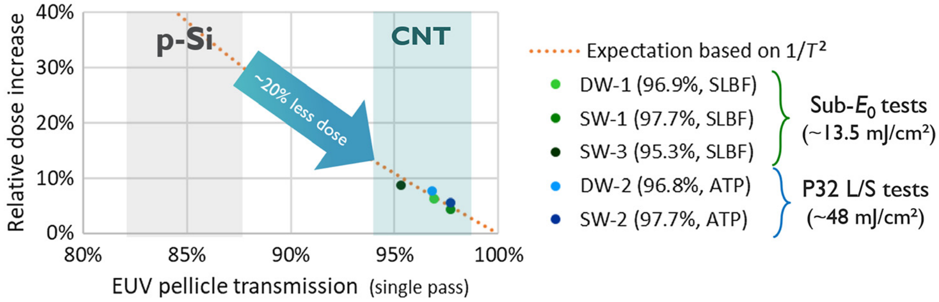


Fig. 3 Relative dose increase versus pellicle EUV-T. The dose increase for the CNT pellicles is in line with the expectation.

of a pellicle on a mask will increase the required exposure dose. In turn, this reduces the scanner throughput (TPT). The major advantage of CNT pellicles is their high transmission, and therefore a smaller impact on the exposure dose is expected compared with poly-Si pellicles. With single-pass pellicle transmission (T), a simple theoretical expectation for the relative dose increase is given by $(1/T^2 - 1)$. In this approximation, an ideal pellicle with 100% T has no associated dose increase, while a pellicle with 85% T leads to 38% dose increase.

In our experiments, which are further described in following sections, we found the dose-to-size increase ranging between 4% and 9%, depending on the pellicle transmission. As shown in Fig. 3, these findings are in line with the theoretical expectation based on $1/T^2$. When compared with poly-Si, CNT pellicles can reduce the exposure dose by ~20%. This reduction of the actual exposure time will bring benefit to the scanner TPT. The exact impact is modulated by the percentage of scanner overhead time.

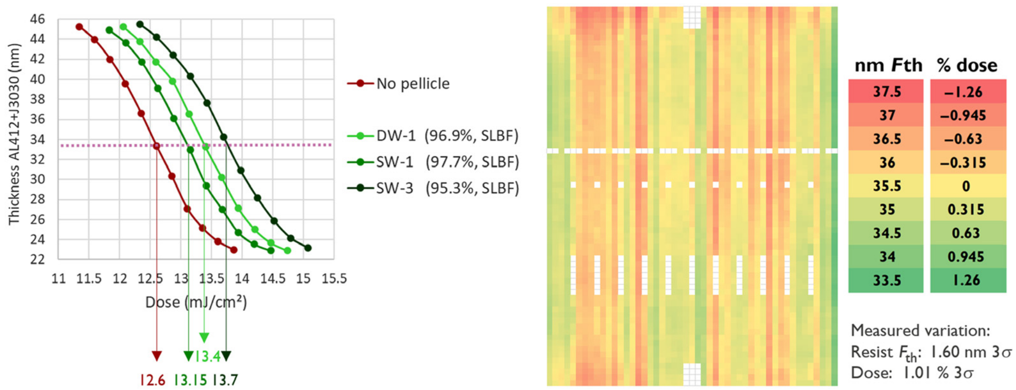
2.3 *Impact of CNT Pellicles on the Intra-Field Uniformity*

The CNT pellicle film not being sufficiently uniform over the full field, e.g., in its EUV-T, would contribute to intra-field non-uniformity in resist. Specifically, it would contribute to the dose variation over the exposure field. In this section, we report intra-field data obtained from both masks in this study by sub-E_0 measurements and CD-SEM measurements, respectively. In particular, we evaluate the change from the intra-field data without a pellicle to that with a pellicle. In the ideal case, the addition of a pellicle only impacts the dose-to-size, without introducing variation within the field.

2.3.1 *Sub-E_0 intra-field measurements*

In this section, we assess the impact of the CNT pellicle on the intra-field map of the dose-to-clear in resist. This is done using the SLBF mask, which is dominantly bright-field (large unpatterned multilayer mirror area). Figure 4(a) shows contrast curves of residual resist film thickness (F_{th}) versus applied exposure dose for the cases with and without a pellicle. The data are the average resist thickness (+20-nm underlayer) within the field, obtained using ASML YieldStar 250. The addition of the pellicle shifts the contrast curves to higher dose values. The ratio of the dose with a pellicle versus the dose without a pellicle determined the relative dose increase in Fig. 3.

At the respective center of the contrast curve (where the sensitivity is highest), a detailed measurement is performed to obtain the intra-field map of the residual resist thickness F_{th} for each of the cases with and without a pellicle. An example of such an intra-field map is shown in Fig. 4(b). This is essentially a fingerprint of intra-field intensity variation caused by the scanner, the reticle, and the pellicle (if applied). The sub-E_0 technique is a very sensitive technique, i.e., capable of detecting very small changes in resist thickness.[12,13] By averaging over 16 dies, non-systematic components such as noise were further reduced. The distinct stripes through scan, as seen in Fig. 4(b), were caused by small through-slit non-uniformity on the NXE:3300B scanner at imec. The two color scales in the figure indicate the magnitude of the variation. One scale



(a) (b)

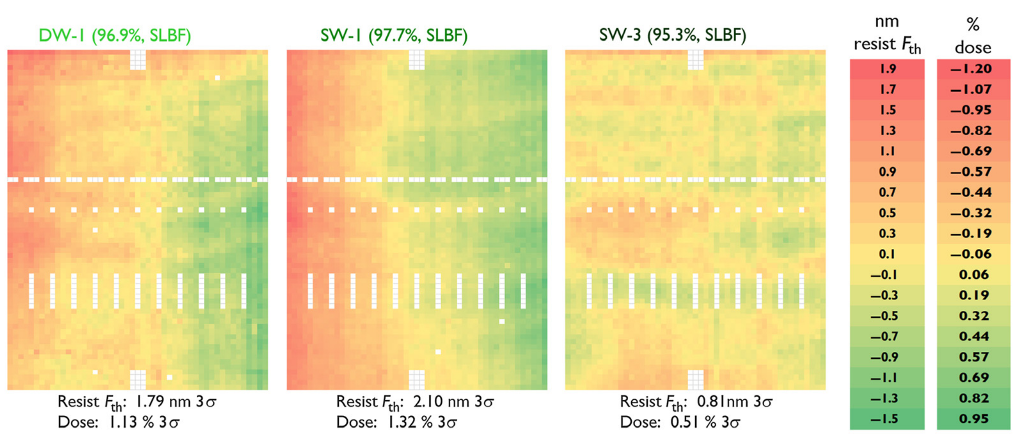
Fig. 4 (a) Contrast curves with and without CNT pellicle. (b) Example of an intra-field sub-E_0 map, measured at the center of the contrast curve slope (26×33 mm^2, sampling interval 500 μm, average of 16 dies). Measurements were not possible at the white locations because those contained absorber patterns at the location of the YieldStar spot (30-μm spot size).

expresses the resist F_{th} variation in nm, as measured. The other scale expresses the same variation in an equivalent percentage dose. The translation between them is straightforward because the local dose and F_{th} have a linear relation near the center of the contrast curve, through the slope of 0.63% dose per nm resist F_{th}.

Ideally, the scanner and reticle contributions to the intra-field fingerprint remain stable over the different exposure slots with and without pellicles. Under that assumption, we can evaluate the contribution of the pellicle to the intra-field non-uniformity by subtracting the intra-field resist F_{th} map without a pellicle from those with a pellicle. The result of this delta "with-without" pellicle is shown in Fig. 5 for the double-walled pellicle DW-1 and single-walled pellicles SW-1 and SW-3, respectively. With equal color scales for all three cases, we see that the fingerprint for SW-3 is the flattest and DW-1 and SW-1 dominantly have a gradient from left to right.

Rather than the variation of the resist F_{th} itself, it is of interest to consider the dose-equivalent variation of these delta maps. With only 0.5% 3σ dose variation for pellicle SW-3, the difference between the intra-field fingerprints with and without a pellicle is very small. For pellicles DW-1 and SW-1, the value is slightly higher at 1.1 to 1.3% 3σ, mainly due to the observed gradient.

Ideally, these delta maps would represent the impact of only the pellicle. However, we can still recognize some local stripes through scan, as well as some smiley-curved horizontal patterns



(a) (b) (c)

Fig. 5 Delta between intra-field sub-E_0 maps with and without CNT pellicle. [26×33 mm^2, pixel size $(500\ \mu\text{m})^2$, average of 16 dies per wafer, 2 wafers for each case w/wo pellicle. Same color scale for all intra-field maps.] (a) For DW-CNT pellicle; (b) and (c) for two SW-CNT pellicles. The measured EUV-T values are given between brackets.

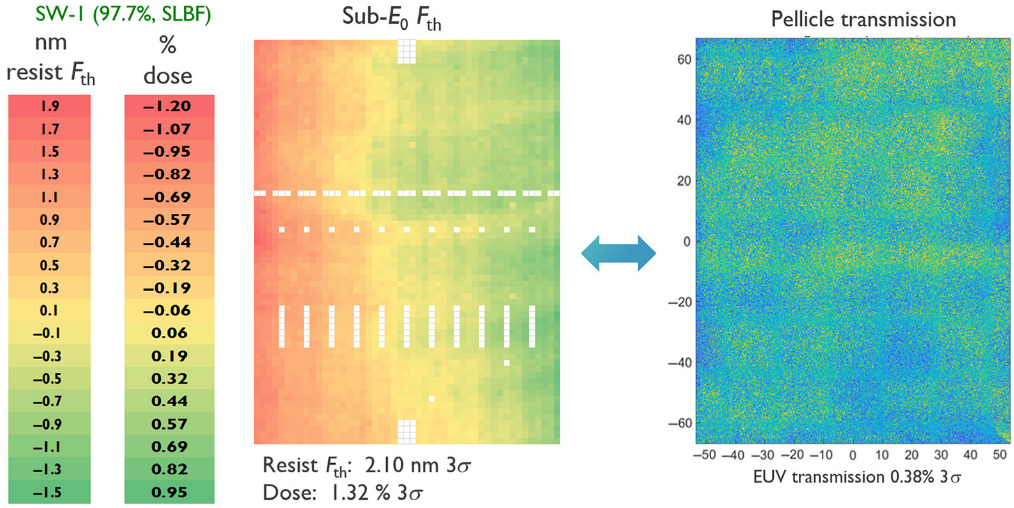


Fig. 6 Change in intra-field sub-E_0 resist F_{th} versus measured EUV-T map for given SW-CNT pellicle SW-1.

typical of the scanner's exposure slit profile. Therefore, we believe that these data also contain some change of the scanner itself in the background, including the observed gradient. It is known to us that the dose performance through slit on the NXE:3300B at imec could exhibit minor changes over time as well as wafer to wafer, such as the change in the dose profile through slit (including a tilt), which would contribute to the left-right gradient of $\sim$1% 3σ.

To further explore this, the above delta maps "with-without pellicle" have been compared with their respective pellicle EUV-T map, which was measured prior to mounting the CNT pellicle on the reticle. In Fig. 6, such a comparison is shown for the pellicle SW-1, i.e., the case for which the largest variation is seen in Fig. 5. However, in our currently available tooling and methodology for full-field EUV-T measurements, the data processing and interpretation are difficult because the metrology artifacts and actual signal can be hard to distinguish in the full-field map. In that sense, we recognize that the transmission map in Fig. 6 may contain some metrology artifacts (e.g., resulting from stitching smaller fields of view). Therefore, a conclusive comparison of the wafer data with the available transmission maps is not trivial. Nevertheless, based on the collected EUV-T data, we believe that this SW-1 wafer data with the strongest gradient in the "pellicle impact" should be more uniform. In other words, we suspect this gradient to largely originate from scanner variation between the exposure moments with and without a pellicle rather than being an effective impact of the pellicle.

Finally, we note that an eventual established fingerprint of the pellicle should be largely correctable by applying the ASML Dose-Mapper function (potentially based on pre-measurement of the pellicle transmission).

2.3.2 *CD intra-field measurements*

In this section, we directly assess the impact of the CNT pellicle on the intra-field CD fingerprint. This is done using the P32 L/S CD-SEM modules that are distributed on our ATP reticle. As described above, measurements of an intra-field fingerprint were performed on wafers exposed without a pellicle and with DW-CNT and SW-CNT pellicles (cfr. DW-2 and SW-2 in Fig. 2). Before measuring the detailed intra-field CD fingerprint, the wafers were targeted to print the P32 L/S at an average line CD of 16 nm and at best focus. The dose-to-size was found at 45, 48.5, and 47.5 $\mathrm{mJ/cm^2}$ for the cases without a pellicle, DW-2 (EUV-T 96.8%), and SW-2 (EUV-T 97.7%), respectively. The ratio of the dose with and without the pellicle determined the relative dose increase as shown in Fig. 3. From these targeting wafers, the sensitivity of the CD to dose was determined. This dose sensitivity was found to be 0.36 to 0.37 $\mathrm{nm/(mJ/cm^2)}$, from which it can be derived that a $\sim$6.1% dose change is required to induce a CD change of 1 nm. Within the precision of this determination, no impact was found by applying a pellicle. In other words, the

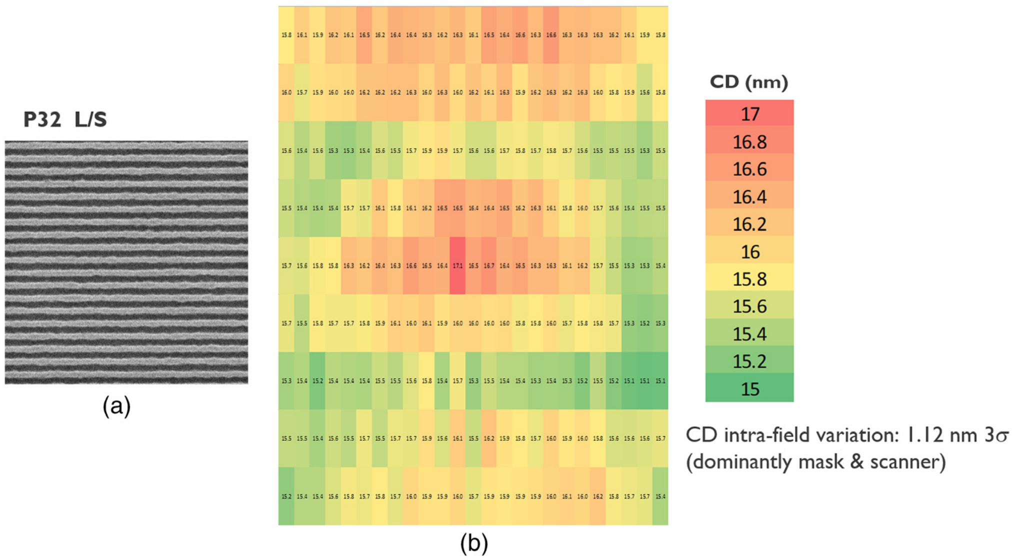


Fig. 7 (a) Horizontal P32 L/S pattern measured at 25×9 positions within the exposed field. (b) Example intra-field line CD map ($26 \times 33\ \mathrm{mm}^2$, average of 20 dies).

addition of the CNT pellicle was not found to impact the exposure latitude. An example of a CD map with sampling 25×9 is shown in Fig. 7 (without a pellicle). The CD variation of 1.1 nm 3σ is dominantly originating from the mask and the scanner.

Again, the impact of the pellicle on the intra-field CDU is investigated by subtracting the no-pellicle map from those measured with the CNT pellicle. The resulting delta maps are shown in Fig. 8, respectively, for pellicles DW-2 and SW-2. At 0.2 nm 3σ, the observed impact of the pellicle on the intra-field CD is very small. Using the determined sensitivity of 6.1% dose per

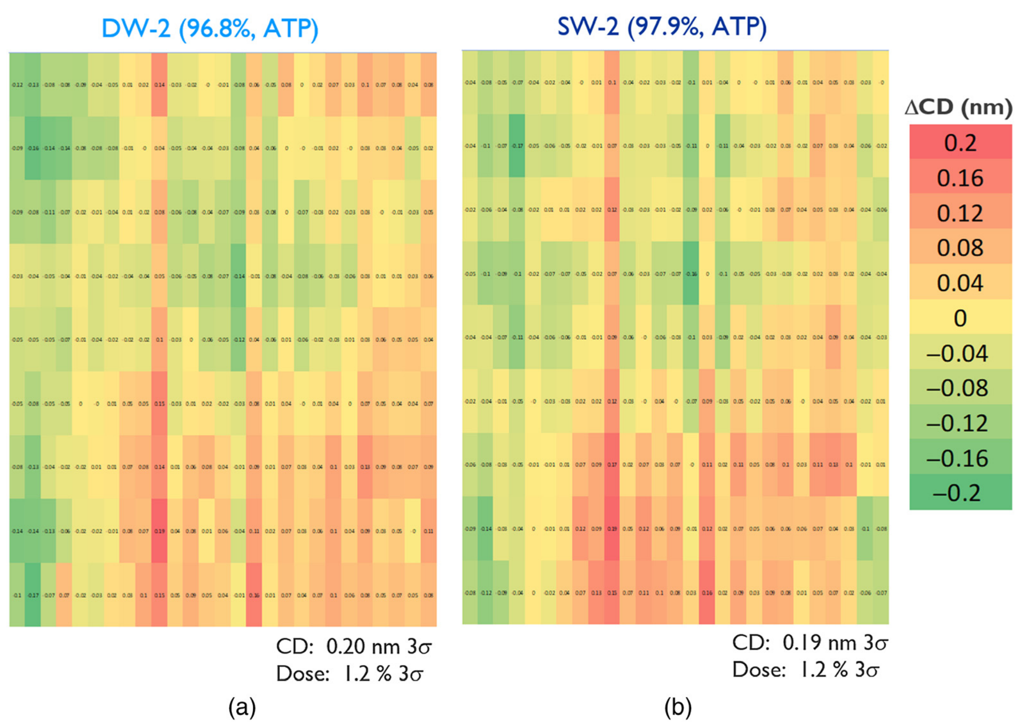


Fig. 8 Delta between intra-field P32 line CD map with and without CNT pellicle ($26 \times 33\ \mathrm{mm}^2$, average of 20 dies for each case w/wo pellicle. Same color scale for both maps). (a) For DW-CNT pellicle and (b) for SW-CNT pellicle. The measured EUV-T values are given between brackets.

nm CD, the dose-equivalent variation is 1.2% 3σ, which is in line with what was found with the sub-E_0 tests for these pellicle types on the SLBF mask in the previous section (cfr. Fig. 5).

Looking at the delta maps in Fig. 8, the pellicle impact is again somewhat "polluted" by a scanner variation component. In particular, through-slit instabilities causing distinct vertical stripes through scan can be recognized in both delta maps;, these cannot be easily removed. Therefore, the obtained impact of 1.2% dose 3σ also includes scanner variation over time. We estimate that the variation due to the addition of the CNT pellicle is below 1% dose 3σ.

2.4 *Impact of CNT Pellicles on the Line Width Roughness*

The CD result for the P32 L/S in the previous section was obtained from many SEM images. In total, over 165k lines were measured for each pellicle case. On these lines, the raw line width roughness (LWR) also was determined and compared with and without a pellicle. It should be noted that resist and illumination conditions were not optimized to achieve low LWR in our tests.

The data in Fig. 9 shows that the addition of the CNT pellicles has little impact on the measured LWR. Also, from process window measurements on the wafers with and without a pellicle, we did not see a noticeable impact of the CNT pellicle on the exposure latitude. This confirms that the CNT pellicle conserved the image contrast.

2.5 *Impact of CNT Pellicles on Flare*

In our experiments, we observed that roughness and exposure latitude do not deteriorate by the addition of a CNT pellicle. We therefore expect that the scattering from the uncoated CNT pellicles would not significantly increase the flare. Also, in tests where CNT membranes were placed between an EUV source and a CCD detector, scattering was found to be low for uncoated pellicles.[8,9] Scattering simulations indicate that the scatter depends on the type of CNT (single-, double-, or multi-walled), on bundling (number of CNTs per bundle), and on density (e.g., higher density will increase scatter and decrease EUV-T). It should be noted that scattering from coated pellicles is expected to increase compared with uncoated pellicles.[9]

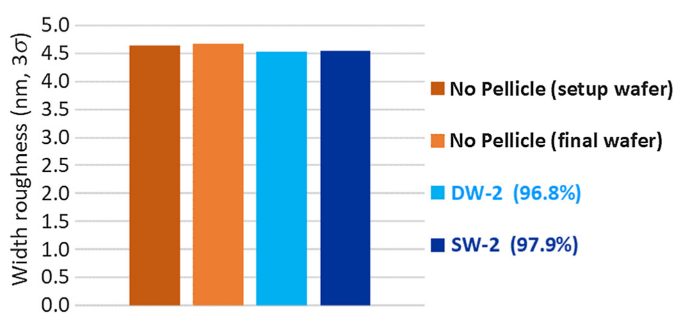


Fig. 9 Raw line width roughness for the P32 patterns, without pellicle and with double-walled and single-walled pellicles.

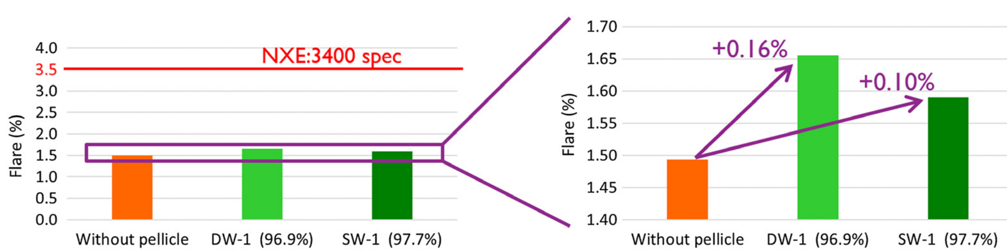


Fig. 10 Measured EUV flare, without a pellicle, and with DW-CNT and SW-CNT pellicles (output of NXE SAMOS test, for 37-μm pad, averaged through slit). The measured EUV transmission values are given between brackets.

SAMOS is the default flare test on ASML NXE systems, measuring stray light from multiple opaque squares. Since DUV light is not visible to the sensor in this test, only EUV flare is measured. From multiple available pad sizes, the smallest pad (37 μm) is most sensitive. The specification for maximal flare level measured on this pad is 3.5% for the NXE:3400. To achieve increased precision through averaging, we ran fivefold repetitions of the test for each case without and with a pellicle. Since no slit-dependency was seen, we also averaged the data from 11 measurement locations through slit.

As illustrated in Fig. 10, our tests showed a very small increase of 0.16% and 0.10% (absolute values) by adding a double-walled and a single-walled pellicle, respectively. These values are in line with the measurements described in Ref. 9 and listed in Fig. 1, confirming that scattering from uncoated CNT pellicles is very small. In our tests, either with or without CNT pellicle applied, the measured flare remained far below the 3.5% spec.

3 Conclusion

This paper describes the results of the first full-field CNT pellicle exposure on an EUV scanner. It demonstrates the ability to fabricate and handle full-field CNT pellicles without breakage. Multiple single-walled and double-walled uncoated CNT pellicles with EUV-T of up to 97.7% were exposed.

The impact on the imaging is found to be minimal. The required exposure dose increases in line with the expectation based on the EUV-T, e.g., for the pellicle with the highest transmission of 97.7% (single-pass), the exposure dose only increases by 4%. The high EUV-T of the CNT pellicles therefore allows higher scanner TPT compared with other pellicle types that have lower transmission. The impact of CNT pellicles on the intra-field CD uniformity was found to be less than 0.2 nm 3σ for given P32 L/S pattern, which corresponds to a dose-equivalent non-uniformity of about 1% 3σ. No increase in line width roughness was seen upon addition of the CNT pellicles, and the exposure latitude was conserved. A small flare increase of 0.10% to 0.16% confirms that scattering is minimal on uncoated CNT membranes.

These first full-field CNT pellicle exposures were intended to demonstrate handling of the pellicles in the EUV scanner and were a first assessment of their imaging behavior. To this end, uncoated CNT pellicles were used; they are not expected to meet the lifetime target under current scanner conditions. Therefore, current ongoing development focuses on pellicle optimization for durability in the scanner environment.[9,11] The presented demonstration proves the value of a CNT-based EUV pellicle solution.

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References

1. R. Hershel, "Pellicle protection of integrated circuit (IC) masks," *Proc. SPIE* **275**, 23–28 (1981).
2. I. Sakurai et al., "Pellicle for ArF excimer laser photolithography," *Proc. SPIE* **3748**, 177 (1999).
3. L. Van Look et al., "Pellicle contribution to optical proximity and critical dimension uniformity for 1.35 numerical aperture immersion ArF lithography," *J. Micro/Nanolith. MEMS MOEMS* **10**(1), 013009 (2011).
4. M. Y. Timmermans et al., "Free-standing carbon nanotube films for extreme ultraviolet pellicle application," *J. Micro/Nanolith. MEMS MOEMS* **17**(4), 043504 (2018).

5. E. E. Gallagher et al., "CNT EUV pellicle: balancing options," *Proc. SPIE* **11148**, 111480Z (2019).
6. D. Brouns et al., "Pellicle HVM specifications," Pellicle TWG, San Jose (2016).
7. D. Brouns et al., "Pellicle industrialization update," in *25th Symp. Photomask and NGL Mask Technol.* (2018).
8. I. Pollentier et al., "The EUV CNT pellicle: balancing material properties to optimize performance," *Proc. SPIE* **11323**, 113231G (2020).
9. I. Pollentier et al., "EUV scattering from CNT pellicles: measurement and control," *J. Micro/Nanopatterning Mater. Metrol.* **20**(4) (2021).
10. M. Keshet et al., "Enabling non-actinic EUV mask inspection using carbon nanotube pellicle," *Proc. SPIE* **11609**, 1160910 (2021).
11. M. Y. Timmermans et al., "Carbon nanotube EUV pellicle tunability and lifetime," *J. Micro/Nanopatterning Mater. Metrol.* **20**(4) (2021).
12. L. Van Look et al., "Optimization and stability of CD variability in pitch 40 nm contact holes on NXE:3300," *Proc. SPIE* **10809**, 108090M (2018).
13. V. V. Nair et al., "Accurate mapping of dose variations on EUV scanners using dose-to-clear exposures and optical ellipsometry," *Proc. SPIE* **11517**, 115170O (2020).
14. J. Bekaert et al., "CNT pellicles: imaging results of the first full-field EUV exposures," *Proc. SPIE* **11609**, 116090Z (2021).

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Biographies of the other authors are not available.