Experimental Study of Effect of Pellicle on optical Proximity Fingerprint for 1.35 NA immersion ArF Lithography

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ABSTRACT

To ensure defect-free printing, pellicles are mounted on the masks used in optical lithography for IC manufacturing. The pellicle, a thin transparent polymer film, protects the reticle from dust. But, as the 193 nm light transmittance through the pellicle has an angular dependency, the pellicle also acts as an apodization filter.
In the current work, we present both experimental and simulation results at 1.35 NA showing the influence of two types of pellicles on proximity and intra-die Critical Dimension Uniformity (CDU) on wafer. The considered structures are compatible with the 32 nm logic node for poly and metal. For the standard ArF pellicle (thickness 830 nm), we experimentally observe a distinct effect of several nm's of the pellicle presence on both the proximity and the intra-die CDU. For the more advanced pellicle (280 nm thin) no signature of the pellicle on proximity or CDU could be found.
By modeling the pellicle's optical properties as a Jones Pupil, we are able to simulate the pellicle effects with good accuracy. These results indicate that for the 32 nm node, it is recommended to take the pellicle properties into account in the OPC calculation when using a standard pellicle. Simulations also indicate that, in addition to that, a local dose correction can compensate to a large extent for the intra-die pellicle effect.
When using the more advanced thin pellicle (280 nm), no such corrections are needed.

Keywords: Pellicle, optical proximity, Jones Pupil, CDU, Pellicle thickness uniformity

1. INTRODUCTION

In current optical lithography for IC manufacturing, it is very common to use high Numerical Apertures (NA's) ($1 < NA \leq 1.35$). These high NA's are needed to address the resolution requirements of the 32 nm node. The standard pellicles that are used to keep the reticles dust-free are optimized for maximum light transmittance under normal incidence of light. However, in these high NA immersion systems, the incidence of light on the pellicle is oblique, leading to transmission and phase errors for the light passing through it. At the same time, the CD and CD uniformity specifications for these high NA applications become ever tighter, leading to increasing concern of the effects that such pellicles may have on proximity and CDU performance.

In literature, a number of simulation studies can be found where this concern is quantified by simulations, and clear guidelines are provided on how to model the pellicle effects2, 3. As far as experimental wafer data is concerned, there are only few examples and, to our knowledge, none of them are at NA 1.35. The paper4 by Luo et al. contains experimental and modeling data at NA 1.2 showing the pellicle effect for lines through pitch with varying CDs ranging from 55 nm to 65 nm. For the effect of a pellicle on the CDU, we refer to an early evidence5 of CDU increase due to the pellicle presence for 180 nm wide resist lines. In the study6 by Morikawa et al. an increased CDU of 45 nm features (NA 1.4) is measured by AIMS in the presence of a pellicle. However, in none of these studies, a correlation to the pellicle thickness uniformity is made. There is also no data available on the advanced thin 280 nm pellicle.

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With this work, we aim to provide experimental demonstration of the effect of a standard pellicle and a more advanced thin pellicle on both the CD through pitch (proximity) curve and the intra-die CDU fingerprint at 1.35 NA. By verifying the predictive power of the simulations based on measured pellicle characteristics, we also want to show that the pellicle effects can be modeled, and can thus be taken into account during process optimization by pellicle-aware OPC[4,5] and/or (variable) local dose fingerprint application. As the lifetime of a pellicle is much shorter than that of the reticle, replacing the pellicle may lead to different intra-field properties. Variable solutions that are tailor-made to the pellicle properties could provide a solution in this case.
In the remainder of this paper, we will first explain the setup and flow of the experiments we performed. The next Section summarizes how the pellicle effect can be modeled and then simulated using commercially available lithographic simulation software. Section 4 describes the experimental and simulation results for proximity and CD uniformity.

2. SETUP OF THE EXPERIMENT

2.1 Experimental flow

The purpose of these experiments is to show the influence of the 830 nm thick and the 280 nm thin pellicle on the proximity and CDU printing result on wafer at NA 1.35. We therefore placed and removed a thick and a thin pellicle on the same mask. We exposed a set of wafers in the three conditions of the reticle (without pellicle, with thick pellicle, with thin pellicle) at several illumination conditions on an ASML XT:1900Gi scanner, interfaced to a Sokudo RF[3] track. The stack used on all wafers is identical: 95 nm of ARC29SR BARC (Brewer/Nissan) + 105 nm TArF-Pi-6001 resist (TOK).

After removal of the thick pellicle, a mask clean was performed. Reticle SEM measurements ensured that the reticle CDU fingerprint remained identical under such action.

2.2 Reticle design

The reticle used for this work was a 6% attenuated phase shifting MoSi mask with a unit cell that is repeated 13 in the slit and 9 times in the scan direction Figure 1 (right). The unit cell contains large pitch-CD matrices of line and trench structures intended for measurement with CD-SEM. This allows the user to perform a manual bias picking that ensures a constant wafer CD through pitch. The range of available reticle CDs is very broad, such that the reticle can be used to print 45 nm as well as 90 nm features through pitch. A small number of scatterometry marks are also available which were used for YieldStar measurements. There are no assist features present on the mask.

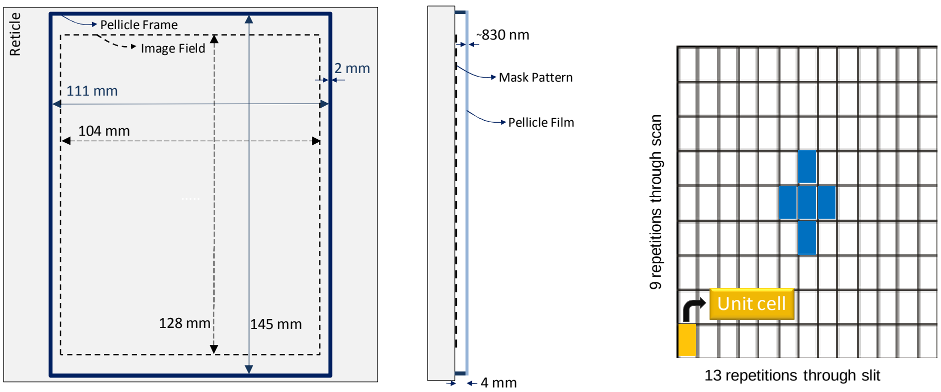

Figure 1. *Left*: Schematic presentation of the reticle with a mounted pellicle (top down and cross-section). Indicated sizes are typical of the standard ArF thick pellicle. *Right*: Layout of the test reticle used for this work. Blue subfields are the ones used for the proximity measurements.

2.3 Pellicle thickness measurements

The thickness map of the 830 nm (thick) and 280 nm (thin) pellicle were measured using an Analyzer 5700-CDRT ellipsometer (N&K Technology, Inc.). The measurement repeatability of this tool on identical locations was verified to be below 0.2 nm 3σ. The pellicle area that was measured covers the image field completely. The frame height was 4 mm for the thick pellicle and 2 mm for the thin pellicle.

The measured thickness map of the thick pellicle has a range of 3.1 nm around an average value of 824 nm. To verify that the thickness fingerprint was stable, we measured the pellicle thickness map before mounting the pellicle frame onto the reticle, and after removal of the pellicle frame. Both measurements yielded an almost identical thickness map (3σ of the difference is 0.3 nm). For the thin pellicle, the measured thickness map has a range of 1.3 nm around an average value of 278 nm.

2.4 Wafer CD measurements

For the *proximity experiments*, we selected an Annular illumination condition, NA 1.35 Annular σ0.64-0.84, XY Polarized. At the start of the experiment, a bias picking was done in order to print lines and trenches to a target of 45 and 90 nm on wafer through pitch. Once these approx. 80 structures were chosen, they remained fixed for the remainder of the experiment. All metrology through pitch was performed using a KLA-Tencor e-CD2 top down CD-SEM. To reduce metrology noise, we averaged over a set of 5 sub dies positioned cross-wise central on the reticle (Figure 1 right).
For the *CDU measurements*, we exposed wafers with three different illumination conditions, amongst which the Annular setting mentioned above. Other conditions used are DipoleY35° σ 0.85-0.98, X Polarized and CQuad40° σ 0.70-0.90, XY Polarized. The CD measurements were mainly performed on an ASML YieldStar S-100. The repeatability of the YieldStar was verified to be 0.07 nm 3σ on identical measurement locations. We also measured multiple wafer CDU maps with the KLA-Tencor e-CD2 top down CD-SEM for comparison.

3. MODELING OF THE PELLICLE EFFECT ON IMAGING

3.1 Angular dependence of pellicle transmittance and induced phase shift

When discussing the possible influence of a pellicle on imaging, the mean concern lies in the usage of large angles of incidence on the pellicle film that are intrinsically linked to the use of high numerical apertures (NA's). At reticle side, the light rays that are used for imaging hit the pellicle film under a maximum angle $\theta = \sin^{-1}\left(NA/4\right)$, which amounts to ~20° for 1.35 NA applications. The pellicle film is typically fully transparent (k~0) for 193 nm light, but has a refractive index of 1.4, causing reflections at its surfaces. The amount of light that makes it through the pellicle and the phase shift this light receives depends on the incidence angle and is given by textbook expressions for homogeneous dielectric films[1]. The standard pellicle, which has a thickness of 830 nm, is optimized for maximal transmission at low angles of incidence (low NA applications), but shows a significant transmission loss for the 193 nm light at oblique angles of 20° (Figure 2). This transmittance loss at high angles is equivalent to an apodization effect, be it that the amount of apodization depends on the polarization state of the light. Besides the thick 830 nm pellicle, we are also considering a more advanced thin pellicle of 280 nm thickness in this work. Figure 2 shows the pellicle transmission as calculated for both pellicles, using a 193.3 nm wavelength. It becomes immediately apparent that the thin pellicle suffers much less from the above-mentioned apodization effects, even at 1.35 NA.

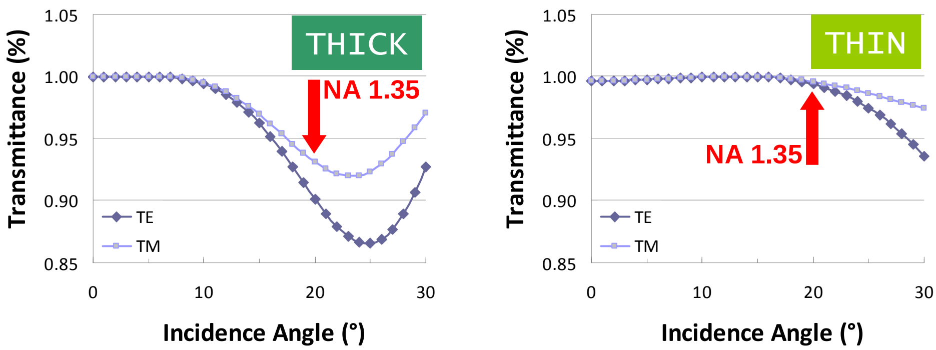

Figure 2. Pellicle transmittance as a function of incidence angle for the 830 nm thick pellicle (left) and for the 280 nm thin pellicle (right).

Because of the different path lengths through the pellicle film for light coming in at different angles, also the phase shift that is brought upon by the pellicle depends on the incidence angle. The calculated phase shift by the pellicle presence is shown in Figure 3 for both the thick and the thin pellicle. The plot shows the phases relative to the phase of the normal beam. These phase shifts are responsible for aberrations (mostly spherical Z9[2,3]) and are again clearly much smaller in the case of the thin pellicle.

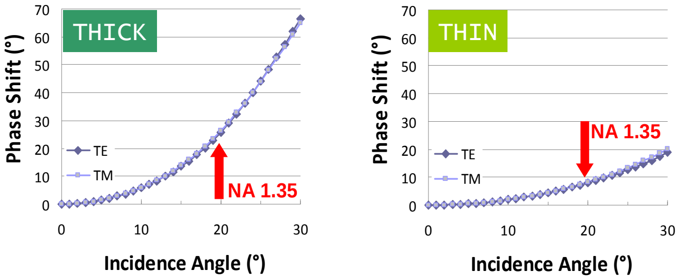

Figure 3. Phase change upon passing through the pellicle film as a function of incidence angle for the 830 nm thick pellicle (left) and for the 280 nm thin pellicle (right).

3.2 Translating pellicle effect to a Jones Pupil

A Jones Pupil describes the polarization-dependent apodization and aberration effects that are induced by the pellicle presence. As nicely explained in literature[2,3], the above calculated transmission and phase change form the diagonal elements of the Jones Pupil in polar coordinates. After transformation to Cartesian coordinates, the cross-terms are no longer zero, implying that there is some intermixing of the two polarization states by passing through the pellicle. However, the found cross-talk terms J_{xy} and J_{yx} turn out to be very small. The Jones pupil acts on the x and y components of the incoming light vector as

$\begin{pmatrix} \overline{E}_x' \\ \overline{E}_y' \end{pmatrix} = \begin{pmatrix} J_{xx} & J_{xy} \\ J_{yx} & J_{yy} \end{pmatrix} \begin{pmatrix} \overline{E}_x \\ \overline{E}_y \end{pmatrix}$, with $\overline{E}_x$ and $\overline{E}_x'$ the x components of the incoming and outgoing Electric field vectors respectively. As we also take the phase changes due to the pellicle presence into account, the Jones matrix elements J_{ii} are complex. Figure 4 depicts the amplitude of one of the Jones Pupil elements J_{xx} for both the thick (830 nm) and the thin (280 nm) pellicle. The scales of both graphs are identical for easy comparison. The Cartesian complex Jones pupil can be imported into standard lithography simulation software to evaluate its impact on the printed CDs. For the calculations presented in this paper, we used the KLA-Tencor Prolith v12.0 software package with a calibrated resist model for the stack that was used.

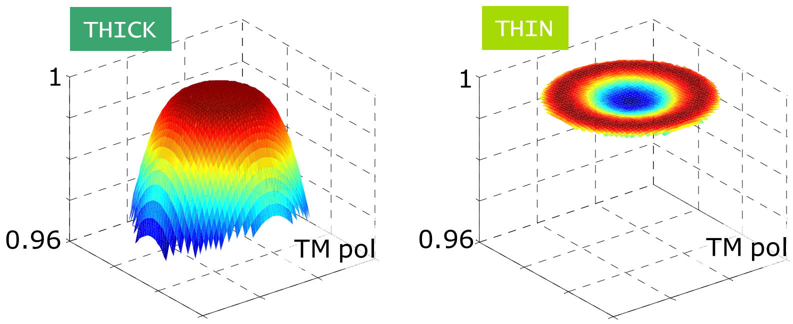

Figure 4. Amplitude of one element J_{xx} of the Jones Pupil, describing the apodization for TM polarized light for the thick (a) and the thin (b) pellicle.

4. EXPERIMENTAL AND SIMULATION RESULTS

4.1 Pellicle effect on Proximity

The same set of structures (line and trench patterns that were picked to print to a resist CD of 45 and 90 nm through pitch) were measured on the wafers exposed with and without the thick and thin pellicle. The apodization effect caused by the pellicle induces a change in the dose-to size. With the thin pellicle mounted, the dose-to-size was equal to that without pellicle. When the thick pellicle was mounted, a 6.5% higher dose was needed to have the same dense structure on reticle print to target on wafer. The same sequence was mimicked in the simulations, where first a set of structures that print to 45 nm and 90 nm through pitch were selected. Next, we constructed the Jones pupils for each of the pellicles using the measured pellicle thickness at the center location of the image field, i.e. at the same location as where the CD measurements are performed. The used values are 822 nm for the thick and 279 nm for the thin pellicle. We then loaded the Jones Pupils for each of the pellicle types and performed a retargeting of focus and dose. For both the experiment and the simulations, we finally subtracted the proximity curves obtained without a pellicle from those measured with the thick and the thin pellicle.

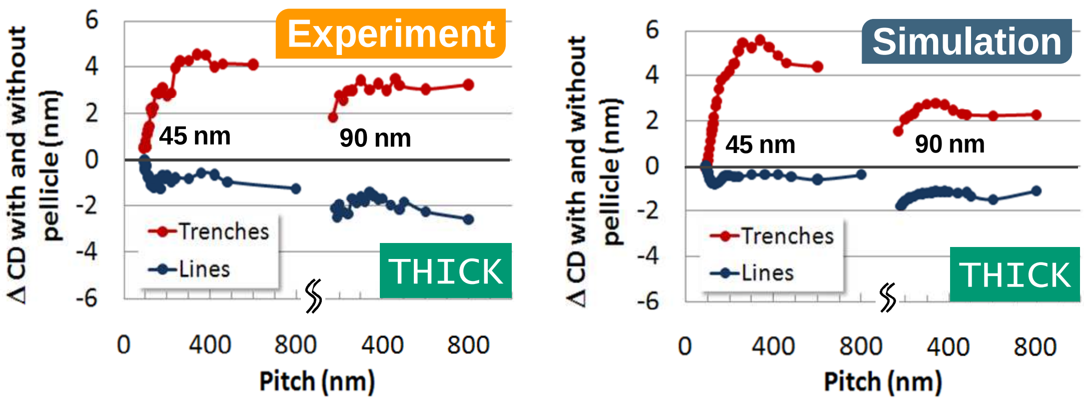

Figure 5. Measured (left) and simulated (right) CD difference through pitch between wafers exposed with and without the thick pellicle. CD differences with and without pellicle of several nm's are observed through pitch.

The obtained CD difference through pitch curves for the thick pellicle are shown in Figure 5 for the experiment (left) as well as for the simulation (right). The thick pellicle presence has clearly changed the proximity curves for both lines and trenches. For lines of 45 nm, experimental pellicle effects up to 1.2 nm can be found through pitch. The proximity curve for the larger 90 nm lines received a shift of about 2 nm over the whole pitch range. For the trenches, the influence of the pellicle on proximity is even higher (up to ~ 4 nm), mainly due to the smaller contrast of these dark field features compared to the lines.

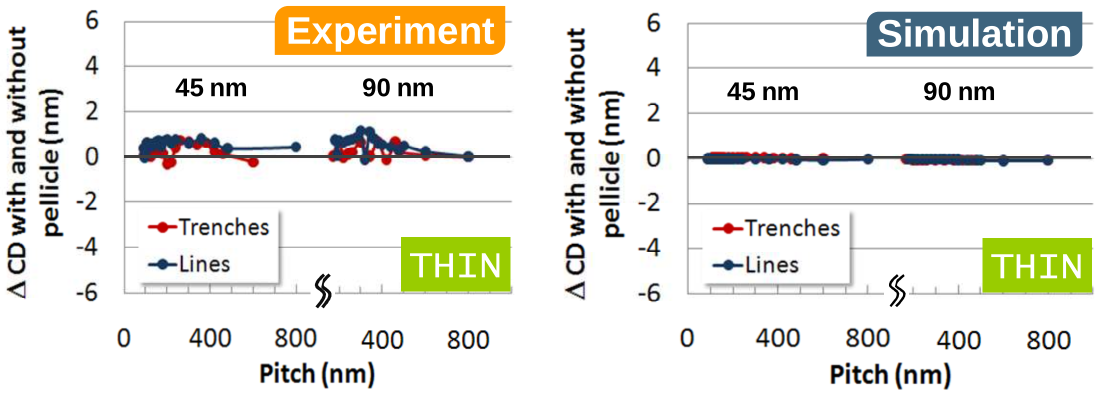

Figure 6. Measured (left) and simulated (right) CD difference through pitch between wafers exposed with and without the 280 nm thin pellicle. The observed CD differences through pitch are below 1 nm.

The simulations using the Jones pupils for the thick pellicle (see Figure 5, right panel) yield very similar proximity differences as the experiment with the same typical characteristics and even very similar amplitudes.
For the thin pellicle, the simulations predict a negligibly small effect. The experiments seem to confirm this trend, although small CD differences (< 1 nm) are observed.

4.2 Pellicle effect on intra-field CDU

Besides the effect the pellicle has on the proximity, we now consider its contribution to the CD uniformity on wafer. The pellicle thickness is not constant over the whole image field. Due to this, the magnitude of the apodization effect also varies over the field. Consequently, identical features at different locations in the field require a different dose-to-size. The measured pellicle thickness map for the thick pellicle showed an average measured value of 824 nm and a range of 3.1 nm, being 0.4 % of the thickness. (upper left panel in Figure 8). The dashed rectangle indicates that part of the measured pellicle area that corresponds to the printed image on wafer. The measured thickness map of the thin pellicle is shown in the lower left panel of Figure 8. The thin pellicle has an average thickness of 278 nm with a range of 1.3 nm (0.5 % of the thickness), which seems mostly due to the corners of the pellicle, i.e. outside the printed field.

The simulated effect of the varying pellicle thickness on the pellicle transmittance is illustrated in Figure 7 for TE polarized light. The green solid lines in these plots are calculated using the nominal pellicle thickness while the solid red curves correspond to the measured average pellicle thickness. The dashed curves around the red solid curve correspond to the actual thickness range that was measured on the pellicle. As is immediately apparent from these plots, the variations in transmittance are much smaller for the thin pellicle than for the thick pellicle.

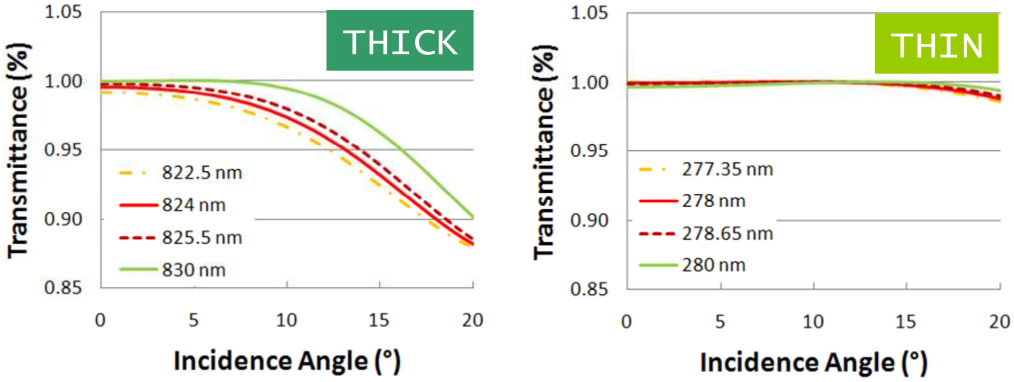

Figure 7. Calculated pellicle transmission for TE polarized light as a function of incidence angle for the nominal pellicle thickness (solid green), for the actual thickness (solid red) and for two thicknesses corresponding to the measured pellicle thickness range (dashed lines).

On top of the smaller observed thickness range for the thin pellicle (1.3 nm versus 3.1 nm), the sensitivity of the wafer CD to 1 nm pellicle thickness change is simulated to be a factor ~5 smaller for the thin pellicle than for the thick pellicle. The expected effect on the intra-die CD uniformity of a thin pellicle can therefore be regarded as negligible.

We now investigate experimentally to what extent the observed pellicle thickness changes affect the CD uniformity on wafer. To this purpose, we subtract the measured wafer CDU maps obtained with and without the pellicle mounted on the reticle. Typical absolute 3σ numbers for the intra-die CD uniformity of the structures we consider here are between 0.9 and 1.4 nm.
The right panels of Figure 8 show the measured effect on the intra-die CD uniformity on wafer of the pellicle presence for a line of 45 nm printed at a pitch of 100 nm. For the thick pellicle (upper right panel), even though the observed CD differences are small (3σ of this difference plot is 0.7 nm), the thickness signature of the pellicle is unmistakably reflected in to the CD uniformity. For the thin pellicle (lower right panel), no correlation between pellicle thickness and CDU difference map (3σ of 0.3 nm) could be found. This is not a surprising result, as the predicted effect of the pellicle thickness changes is negligible. For the considered pellicles, the CD sensitivity for lines to pellicle thickness changes is negative; hence thicker pellicle regions give rise to lower line CDs on wafer.

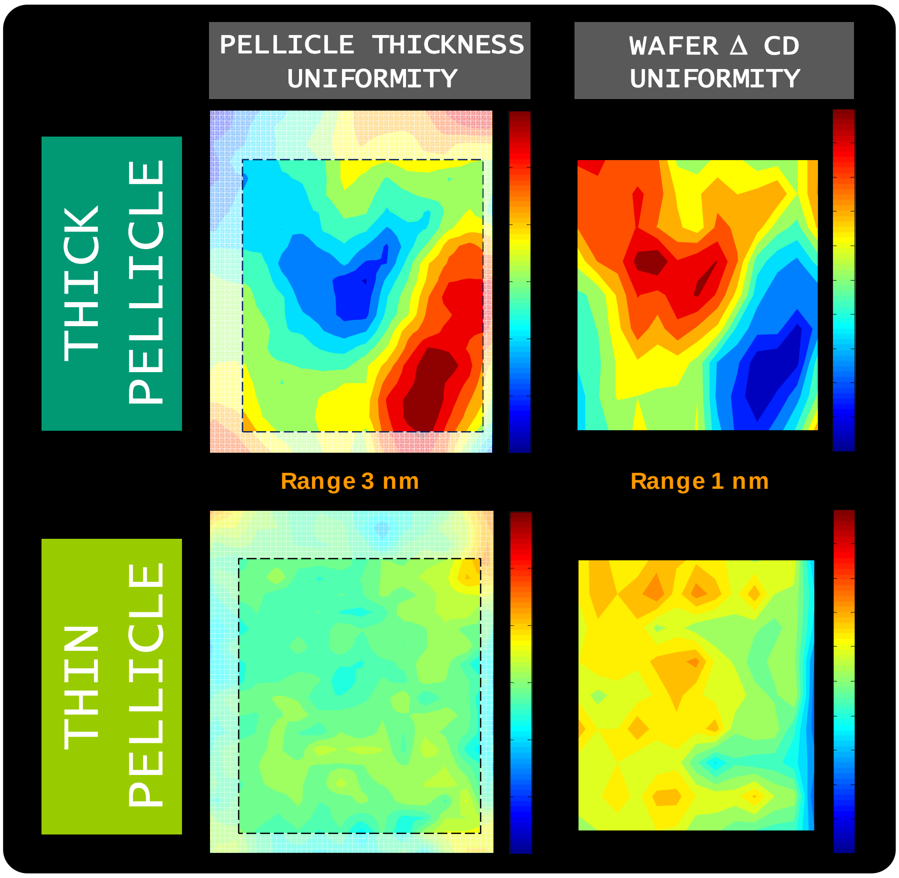

Figure 8. Measured pellicle thickness uniformity maps (left) and their corresponding experimental contribution to the CD uniformity on wafer (right) for a pitch 100 nm line printed using NA 1.35, Annular σ0.64-0.84, XY Polarized illumination.

The CDU difference maps for a pitch 100 nm line (Figure 8) were obtained on wafers exposed using an NA 1.35, Annular 0.64-0.84 XY Polarized illumination setting, and measured with the YieldStar tool. We confirmed the presence of this remarkable CDU difference fingerprint for other features, using other illumination conditions and also using the CD-SEM as a metrology tool (see Figure 9).

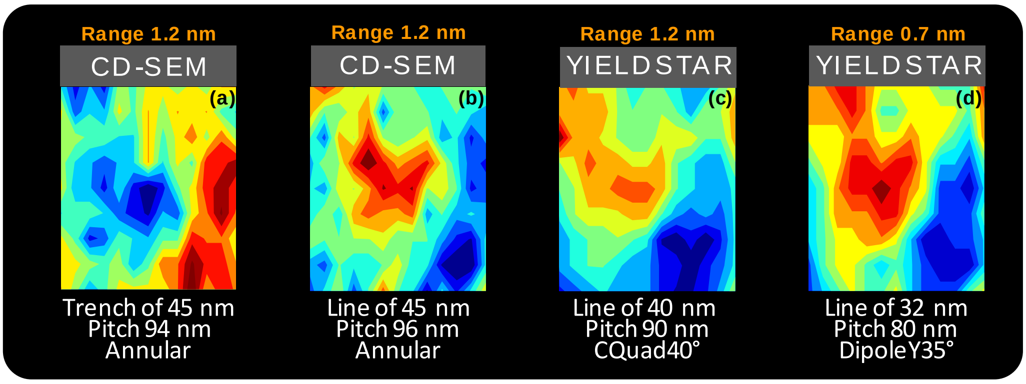

Figure 9. Confirmation of the pellicle influence on the experimental CD uniformity difference maps for multiple features, using different illumination conditions and metrology tools. The apparent shift of the maps is due to the different locations of the features on reticle

The exposure conditions are CQuad40° σ 0.70-0.90, XY Polarized for Figure 9(c), DipoleY35° σ 0.85-0.98, X Polarized for (d). As can be seen in Figure 9(a), trenches react opposite to pellicle thickness changes as lines. The apparent shift in the maps between the different features is due to an offset (up to 2.4 mm (1x)) between their locations on the reticle.

4.3 Compensating the pellicle effect on intra-die CDU with local dose adjustment

As mentioned earlier, the pellicle thickness variations over the field lead to variations in the effective dose-to-size between different locations in the die. If one is able to locally adjust the Dose, using a Dose map that corresponds to the measured pellicle thickness map, the CDU contribution of the pellicle could be minimized. A concern when adjusting dose locally for one feature may be the effect of this Dose change on other features through pitch.

To examine the feasibility of correcting for the pellicle CDU effect of the thick pellicle using a local Dose map, we first simulate the effect on CD through pitch induced by 1.6 nm thickness change at a constant Dose (Figure 10, left panel). This amount of pellicle thickness variation is the one that is present on the thick pellicle we have used for our experiment and also the illumination condition is identical.

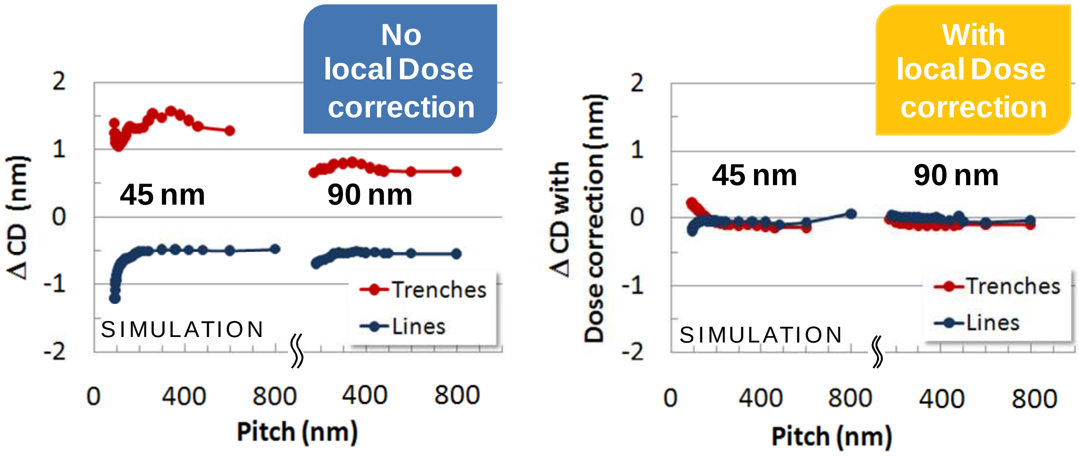

Figure 10. Through-pitch CD simulation of the effect of a local pellicle thickness change of 1.6 nm (left) and its compensation using a local Dose adjustment (right). Results are for a thick pellicle.

When we now use the Dose to compensate for the effect of this pellicle thickness variation, the through-pitch 'penalty' turns out to be quite small. All features (lines and trenches, 45 nm and 90 nm) come much closer to target. There is some remaining apodization effect for the dense 45 nm features that cannot be tuned away using the Dose knob, but overall, the situation is much better with than without the Dose correction.

For the current example, the amplitude of the Dose correction that was applied to compensate for the ± 1.6 nm pellicle thickness change is ± 0.75 % of the nominal Dose.

5. CONCLUSIONS AND RECOMMENDATIONS

We performed an experimental and simulation study of the effect of a pellicle on the proximity and on the intra-die CDU fingerprint at NA 1.35. We examined two pellicle types: the standard 830 nm thick pellicle, and a more advanced 280 nm pellicle. Through their effect on transmission and phase at high incidence angles, these pellicles act as an apodization filter.

Clear evidence (up to ~4 nm for trenches) of the pellicle *effect on proximity* was found for the thick standard pellicle. For the thinner pellicle of 280 nm, the measured effect was much smaller (<1 nm).

For the 830 nm pellicle, we also found an obvious trace of the pellicle thickness map (range 3.1 nm) in the *intra-die CDU fingerprint*, with a pellicle contribution to the CDU on wafer of about 1 nm. As the life-time of a pellicle is much shorter than that of the reticle, the pellicle contribution to CDU will change when replacing the pellicle. In this case, one may consider a correction strategy using local Dose mapping to minimize the pellicle contribution to the CDU. The

through-pitch penalty of such approach was simulated to be quite small. For the thin pellicle, the influence of the pellicle on the intra-die CDU was close to zero and it could not be correlated to the thickness map of the thin pellicle.
The simulations, in which the effect of the pellicle is described as a Jones Pupil, are in good agreement with the experimental results. When thick (830 nm) pellicles are used, we therefore recommend taking the nominal pellicle properties into account during the Optical Proximity Correction.

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