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Focus Drilling for Increased Process Latitude in High-NA Immersion Lithography

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ABSTRACT:

In this paper we discuss a laser focus drilling technique which has recently been developed for advanced immersion lithography scanners to increase the depth of focus and therefore reduce process variability of contact-hole patterns. Focus drilling is enabled by operating the lithography light-source at an increased spectral bandwidth, and has been made possible by new actuators, metrology and control in advanced dual-chamber light-sources. We report wafer experimental and simulation results, which demonstrate a process window enhancement for targeted device patterns. The depth of focus can be increased by 50% or more in certain cases with only a modest reduction in exposure latitude, or contrast, at best focus. Given this tradeoff, the optimum laser focus drilling setting needs to be carefully selected to achieve the target depth of focus gain at an acceptable contrast, mask error factor and optical proximity behavior over the range of critical patterning geometries. In this paper, we also discuss metrology and control requirements for the light-source spectrum in focus drilling mode required for stable imaging and report initial trend monitoring results over several weeks on a production exposure tool. We additionally simulate the effects of higher-order chromatic aberration and show that cross-field and pattern-dependent image placement and critical dimension variation are minimally impacted for a range of focus drilling laser spectra. Finally, we demonstrate the practical process window benefits and tradeoffs required to select the target focus drilling laser bandwidth set-point and increase effectiveness of the source-mask solution for contact patterning.

Keywords: ArF immersion lithography, depth of focus, resolution enhancement, process latitude, excimer laser

I. INTRODUCTION

Double-patterning ArF immersion lithography continues to advance the patterning resolution and overlay requirements and has enabled the continuation of semiconductor bit-scaling. In order to pattern a range of 2D structures at the minimum resolution, high-NA lithography often results in process performance that is limited by the available depth of focus (DOF), particularly for patterning of contacts, vias or trenches. Achieving sufficient overlapping DOF over a range of geometries can be particularly challenging for these applications. This DOF constraint can lead to significant pattern variability, particularly when wafer topography and the overall focus budget is considered. Therefore, lithographers today employ a range of design, process and resolution enhancement techniques to overcome the depth of focus and other variability constraints required for manufacturability of sub-45 nm half-pitch technologies.

In this paper we present a method for increasing the DOF of contact or via patterns using the light-source, which is designed to minimize the reduction in exposure latitude. To illustrate this effect, Figure 1 shows the scanner aerial image-sensor measurement through focus as the laser spectral bandwidth (E95) is switched from a low to high setting, resulting in an observed increase in the depth of focus.

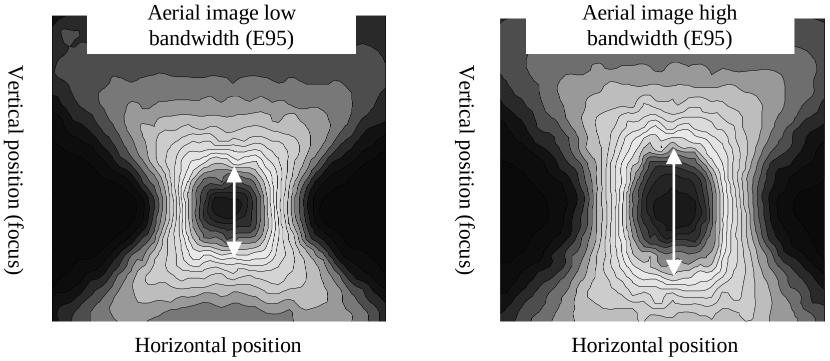

Figure 1. Image-sensor measurement of intensity through focus for low E95 (nominal) and high E95 (focus drilling)

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Various methods of "drilling" through focus have been considered in the past in order to increase the lithographic depth of focus (DOF).[1,2] For example, in step-and-repeat systems the stage can be step-wise or continuously moved in the z-direction during field exposure, while in scan-and-repeat systems the stage (or image slit) can be tilted at a constant angle along the slit axis during exposure. An alternative method has been developed, as discussed in this work, which makes use of the changes in the laser bandwidth to enlarge the depth of focus. An advantage of this approach is that the wafer stage operation is not affected and scanning is performed with no additional movement in the z-direction, which is particularly beneficial for high-productivity immersion lithography.

1.1 Depth of Focus (DOF) Enhancement

An example aerial image response through-focus for a 32 nm logic technology contacts, obtained using a commercial lithography simulator, is shown in Figure 2 below for immersion 1.35NA soft-Quasar® illumination. Here the maximum image modulation, or maximum image contrast, occurs at a defocus of 0 nm and decays (quadratically) as the defocus increases.

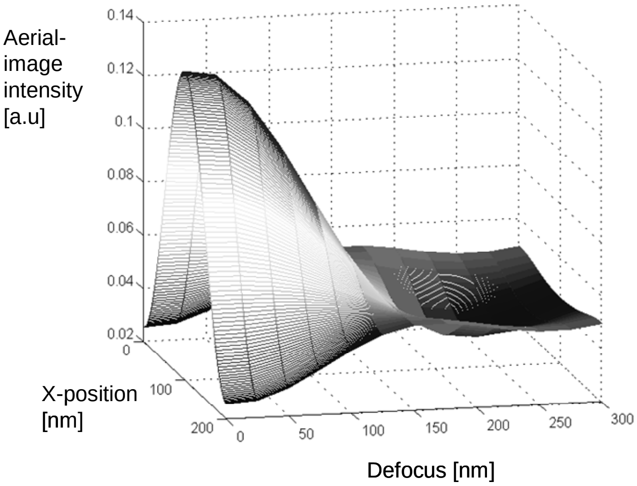


Figure 2. Example lithographic aerial image response through focus; 1.35NA ArFi

In this example the aerial image modulation at a 150nm defocus is minimal and a further increase in defocus results in image reversal, whereby an image minimum is observed at the location of the image maximum at best focus. Therefore in order to increase the image contrast out of focus, any focus drilling approach, must increase the intensity of the images for specific regions of defocus and minimize the contribution of images where image contrast is too low, or image reversal occurs. Since defocus is proportional to wavelength offset,[3,4] in lithographic exposure systems, this can be achieved using changes in the bandwidth of the light-source. The spectrum of the light-source will therefore have a significant impact on the exact amount of contrast enhancement out of focus. The specific choice of light-source actuators, and metrology described in this work is chosen to maximize the DOF enhancement and minimize the contrast reduction from spectral intensities in the low-contrast or image-reversal regions. The ability to control and stabilize light-source operation in the focus drilling mode is critical to ensure stable imaging performance (see reference 5 for more details).

1.2 Focus Drilling Application

The application of focus drilling is targeted for 2D dark-field patterns where the DOF is most constrained and also to enable a maximum process window overlap for multiple pattern geometries. Focus drilling would typically be applied to contact-hole, via or trench patterning. In addition to increasing the overlap process window, this approach may also provide additional degrees of freedom for an optimized OPC solution[7] and potentially relaxed mask requirements.

In the current implementation, laser focus drilling is activated from the scanner exposure recipe with a specific set-point and control value. This drives the light-source to operate and stabilize operation at the desired set-point bandwidth, which is entirely automated enabling equivalent system performance and stability as for nominal laser operation. No additional user interaction with the laser is required to enable focus drilling exposure.

1.3. Light-source Operation

Recent advancements in two-chamber master-oscillator power-amplifier (MoPa) light-sources have enabled new concepts for focus drilling implementation. Current approaches include the design of new actuation within existing line narrowing modules to enable fast and continuous spectral width adjustment and stabilization. The new actuators are applied using existing optical elements, which results in enhanced light-source stability in both nominal and focus drilling modes.

Accurate light-source stabilization for focus drilling requires new advancements in spectrum metrology and compensation schemes which stabilize lithographic CD, dose-to-size, focus, process window and proximity behavior. New spectrum reconstruction approaches have enabled such advanced control schemes. The metrology and control requirements will be discussed further in this paper in the simulation and experimental results sections. The light-source technology required to enable the focus drilling actuation and spectrum metrology are described in more detail in reference 5.

II. SIMULATION RESULTS

2.1. Process Window (PW) Enhancement

Previously.[2,6,7] various researchers have shown that process window and particularly the depth of focus of 2D contact and via structures can be enhanced by broadening the laser bandwidth. These results have been obtained by simulation and confirmed experimentally for KrF and ArF (dry and immersion) lithography processes using various techniques to experimentally modify the light-source operation or perform multiple exposure passes. In Figure 3, below, we show a process window simulation result for 32nm logic contact / via pattern with 165nm pitch. In this case the ArF immersion numerical aperture is 1.35 with annular illumination.

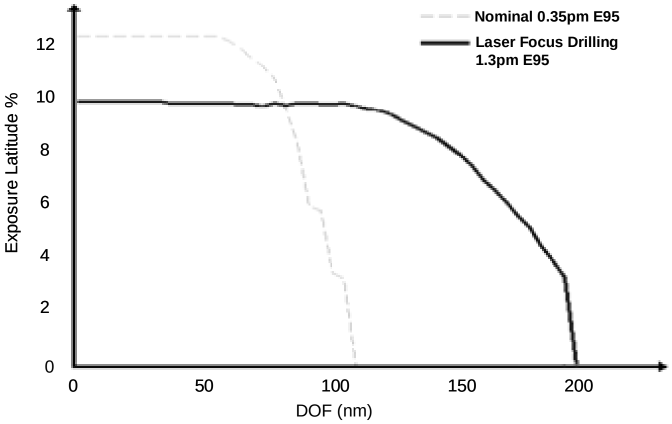


Figure 3. Process window for 1.35NA ArFi exposure for nominal light-source bandwidth (0.35pm E95) and a focus drilling spectrum (1.3pm E95)

For this simulated structure with pitch of 165nm a 60% - 70% DOF increase can be obtained using the Cymer Focus Drilling spectrum (at 1.3pm E95) over the nominal light-source operation (0.35pm E95) at best dose. In this paper, all of the simulations were carried out using Hyperlith or EM-Suite lithography simulation software from Panoramic Technology (http://www.panoramictech.com).

2.2 Focus Drilling Set-point Metrology and Control

The focus drilling set-point for the desired patterning application is selected by considering the overlap process window for all critical geometries that must be resolved simultaneously and defining the focus drilling level at which the required manufacturing focus margin can be met. At the same time the adverse impacts on exposure latitude (contrast loss), mask error factor and proximity effects must be characterized and managed. So far in this paper, we have described focus drilling spectral bandwidths in terms of the industry-standard E95 (95% energy integral) measurement,[8] which is available on board advanced dual-chamber light-sources for monitoring and closed-loop stabilization. This metric is a good predictor of the lithographic imaging performance for nominal light-source operation for control of critical dimension through focus, dose and mask bias.[9]

For the focus drilling application, spectral shape effects become increasingly important as the level of focus drilling increases, and bandwidths above 1pm E95 are required. In Figure 4, we show the CD simulation results for a 32nm logic process at 1.35NA with annular illumination (the corresponding process window for 165nm pitch is shown in Figure 3) for two groups of spectra at 1.2pm E95 obtained experimentally where the variation in spectral shape is maximized (Figure 4-a).

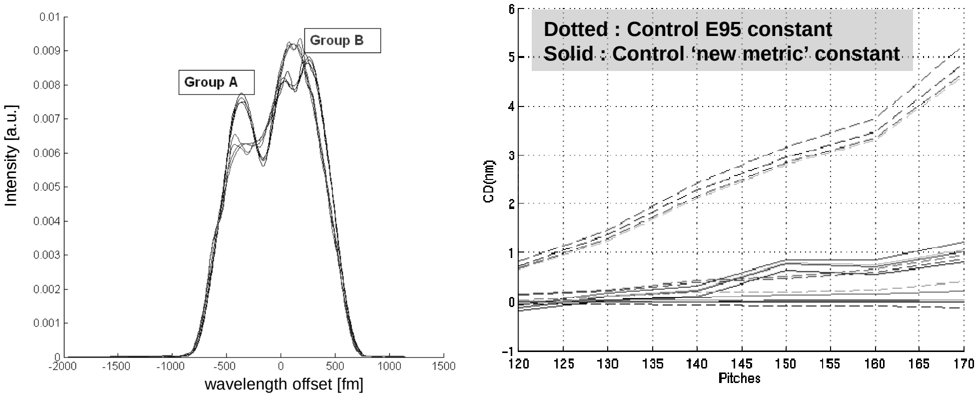


Figure 4. a) Range of experimentally obtained asymmetric spectral shapes, b) CD through pitch due to spectral shape change when spectra are re-scaled to 1.2pm E95 (dotted), or when re-scaled to keep a 'new metric' constant (solid)

For the focus drilling applications, with set-points > 1pm, spectral shape variation leads to changes in proximity effect, which need to be compensated in order to enable stable imaging performance. The bandwidth metrology on-board the light-source must enable full spectrum measurement in order to implement an accurate compensation scheme, as discussed in the next section. One such approach is demonstrated in Figure 4-b, where the dashed lines represent the CD change over the spectral variations shown in 4-a when the width of the spectra is held constant at 1.2pm E95, while the solid lines show the CD change with a new spectral metric constant. Control against this metrics reduces the lithographic variability to sub-1nm over a range of spectral shapes and through focus.

2.3. New bandwidth metric for laser Focus Drilling: Convolved Bandwidth (CBW)

A full-spectral-profile measurement capability has recently been developed that can be integrated with state-of-the-art light-sources for real-time spectral metrology. This is an enabling technology designed to meet the stringent CD control and stability requirements for immersion and double-patterning lithography applications for the focus drilling application. This technology and operational principles are discussed in reference 5. Given that accurate light-source spectral profiles can now be accessed during the operation of the light-source, a choice of metrics can be derived to robustly predict and enable closed-loop feedback for stable lithographic CD performance.

ASML and Cymer have introduced a new bandwidth metric that has very good correlation to the lithographic CD over broad variation in focus drilling spectral shapes and applies for set-points in excess of 1pm. This metric, termed convolved bandwidth (or CBW), is computed as a convolution of a proprietary function with the measured laser spectrum obtained on-board the laser and is used to compute real-time offsets for closed-loop control. An example correlation of the CBW metric to lithographic CD is shown in Figure 5 over a range of spectral shape variation for the 32nm logic imaging condition discussed previously.

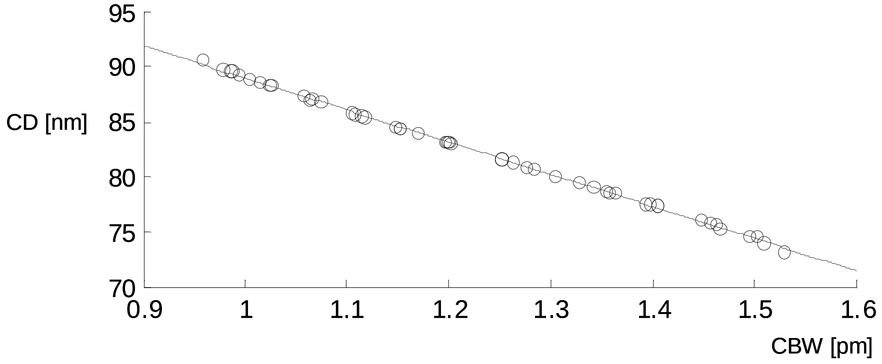


Figure 5. CD - CBW linearity

Although excellent correlation can be achieved with the CBW metric in this range of focus-drilling set-points, for focus drilling levels of 0.5pm to ~1pm, E95 based metrology and control may be preferred due to the diminishing sensitivity of the convolution based metric to changes in bandwidth caused by the characteristic width of the convolution function. The choice of metrology and control schemes based on the new spectrum measurement capability on board state-of-the-art light-sources will be dependent on the specific process application and will be described in a future publication.

2.4. Impacts of Higher-order Aberrations

So far in this work the process window and CD / proximity effect simulations assumed that the chromatic aberrations include only the longitudinal (chromatic defocus) term. Higher-order chromatic aberrations are typically ignored for lithography image calculation considering finite laser bandwidth.[6-11] Although this may be justifiable for nominal light-source bandwidths,[3,12] in this section we evaluate the imaging impacts of higher-order chromatic aberrations in focus drilling mode. The higher order chromatic aberrations Z5(λ) through Z37(λ) (where λ represents the wavelength dependency) for the ASML XT:1700Fi scanner were obtained experimentally and separately confirmed from design data. The simulation results show that the impact of the higher order aberration terms on DOF, EL and IPE are negligible for focus-drilling spectra up to 1.5pm E95. In Figure 6, we see that the difference in calculated DOF is less than 5% when higher-order chromatic aberrations are included compared to using the chromatic defocus term only; similarly the difference in EL is less than 4% and image placement error (IPE) changes by less than 0.2nm.

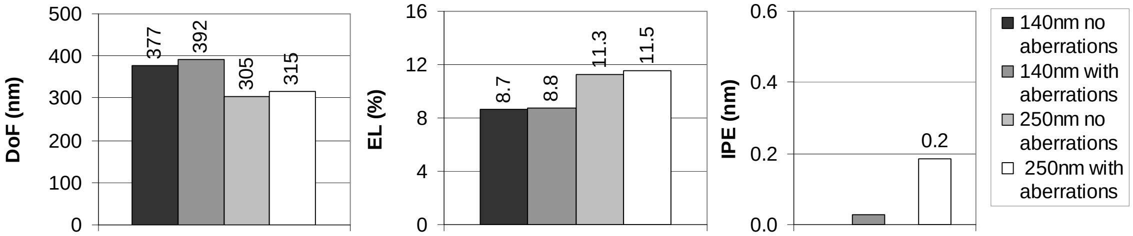


Figure 6. Impact of higher order aberrations on DOF, EL and IPE

The results shown here are for 72nm contact-hole patterns with 140nm and 250nm pitch, for spectra with 1.5pm E95. These simulations were carried out using 1.2NA and the soft annular illumination condition.

III. EXPERIMENTAL RESULTS

In this section we describe the results of wafer experiments validating the DOF enhancement by laser focus drilling. We also consider the impacts on CD uniformity (CDU), exposure latitude (EL), changes in optical proximity behavior and mask error enhancement factor (MEEF) using wafer exposures were obtained on an ASML XT:1700Fi / Cymer XLA™ 360 tool set. We also report on separate results of tool stability monitoring from a production ASML XT:1900Gi scanner in a fabrication facility on which a prototype Cymer XLR™ 560i laser focus drilling modules were installed and operated intermittently with nominal production operation.

3.1. Wafer Experimental Process Window, CDU and Overlay Results

In addition to quantifying the expected depth of focus performance enhancements for a specific patterning application, we experimentally investigate whether any of following side effects occur when switching from low to high bandwidth: (1) focus shift, (2) degradation of exposure latitude, (3) increase in CDU (4) changes in optical proximity behavior, (5) MEEF and (6) overlay, using a prototype laser focus drilling module. The focus drilling prototype was not actively controlled based on laser spectrum metrology feed-back as will be the case in the production version. The wafer exposures reported in this section where carried out on either the Cymer XLA™ 360 light-source and ASML XT:1700Fi or XLR™ 560i and XT:1900Gi with the following process conditions:

- The target CD is 85nm contact hole features, with CD tolerance +/- 10% for process window calculation. The mask targets for pitch in the range of 140nm to 385nm were manually selected for each setting to print at a target of 85nm with dose of 30mJ/cm^2
- In addition to the nominal laser bandwidth of 0.3pm E95, five focus drilling set-points were evaluated with E95 bandwidth of 0.8pm, 1.1pm, 1.2pm, 1.3pm and 1.35pm
- Two illumination conditions were considered: (1) 1.2 NA, with soft-annular 0.86 / 0.66 outer ring, 0.31 sigma and no polarization, and (2) 1.2 NA with annular 0.86 sigma outer and 0.66 inner ring, XY polarized

As expected, an appreciable improvement in depth of focus is observed for all laser focus drilling settings considered, as shown in Figure 7. These results are also compared with a scan-tilt based focus drilling technique, called EFESE™ Rx developed by ASML on its scanners for 500nm and 700nm focus range scan-tilt settings. In terms of focus range, the 500nm scan-tilt setting corresponds to approximately 1.1pm E95 for laser bandwidth and 700nm corresponds to approximately 1.35pm.

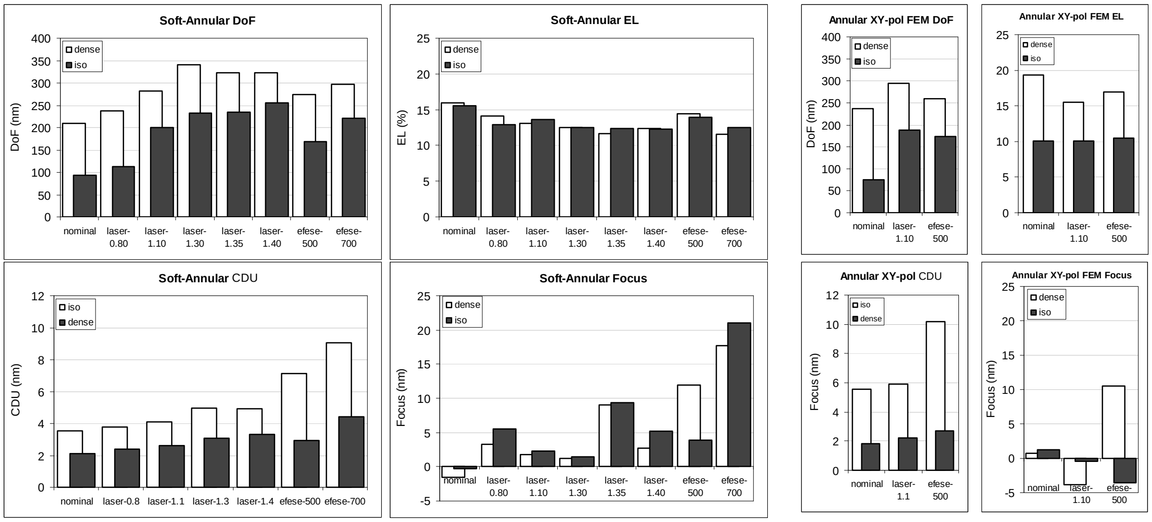


Figure 7. Changes in DOF, EL, CDU and Focus for an 85nm contact-hole process

The largest increase in DOF (62%) is obtained at the 1.3pm FD setting for the dense features with pitch of 140nm and the maximum DOF enhancement for most isolated features with 385nm pitch occurs at 1.4pm E95 (124%). Compared to the nominal laser bandwidth case (0.3pm E95) the corresponding penalty in exposure latitude is limited to 3.5% and 0.6% respectively. The maximum EL degradation through all laser focus drilling settings (0.3pm to 1.4pm E95), is limited to 4.3% for the conditions shown here. At the same time the CDU tradeoff is more severe and degrades by 1nm for dense features, which is still lower than the isolated contact CDU, which limits performance in this process; this may be an acceptable tradeoff if the process window is limited by the process window overlap, and particularly the DOF for isolated structures. The CDU reported here is obtained after removal of average field as well as the cross-wafer fingerprint leaving only the random contribution. Additionally, data in Figure 7 shows that the change in focus offset is well controlled, especially when compared with scan-tilt focus drilling. In table 1 we summarize the changes in process window metrics at the 1.3pm and 1.4pm laser focus-drilling setting for the isolated and dense contact structures.

It is interesting to note that using focus drilling values in excess of 1.1pm and 1.4pm E95 for annular XY-polarized and soft-annular illumination respectively do not result in a further increase in DOF. Beyond this, for the dense features a degradation of the DOF is observed while the EL and CDU remain roughly the same. Depending on the application, loss of image contrast limits the upper bound at which focus drilling can continue to produce an acceptable process window and an increasing DOF. For this data the 1-sigma reproducibility for the DoF and EL measurements is 9.8nm and 0.4% respectively.

	Soft-Annular	Soft-Annular	Soft-Annular	Ann-polarized	Ann-polarized	Ann-polarized
	DoF (nm)	EL (%)	CDU (nm)	DoF (nm)	EL (%)	CDU (nm)
dense (1.3pm)	62%	-3.5	-1.0	24%	-3.8	-0.4
iso (1.4pm)	124%	-0.6	-1.4	151%	-0.1	-0.4

Table 1. Process window metric changes at the 1.3pm FD setting for dense lines

The CD and proximity effect stability of the printed features over a 25-wafer lot was also verified. Figure 8 shows that CDU as well as IDB remain stable throughout the lot and are comparable to baseline system performance with nominal bandwidth of 0.3pm. The variability of CDU and IDB across a lot is <0.25nm.

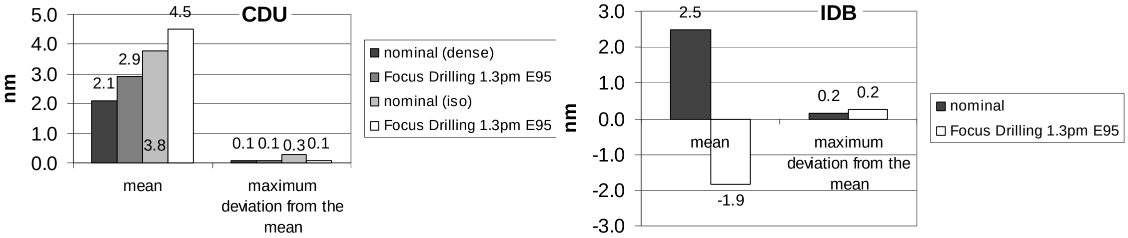


Figure 8. CDU and IDB variability through a lot of wafers

In previous work [12] it has been shown experimentally that the change in image placement error (IPE) from increased bandwidth settings of up to 0.5pm is very small, i.e. less than 0.5nm, for the same exposure tool type. Our simulations for higher-order aberrations described earlier in Section 3 also show negligible contribution to IPE. We have confirmed experimentally that the impact on overlay is quite small for levels of focus drilling up to 1.4pm. The data in Figure 9 shows an experimental result where the overlay error increases by 0.4nm when the 1st lithography layer is exposed using a nominal bandwidth setting of 0.3pm E95 (3.7nm) and 2nd layer exposed at a focus drilling set-point of 1.4pm E95 (4.1nm); both of these overlay exposures were carried out on the an XT:1900Gi / XLR 560i.

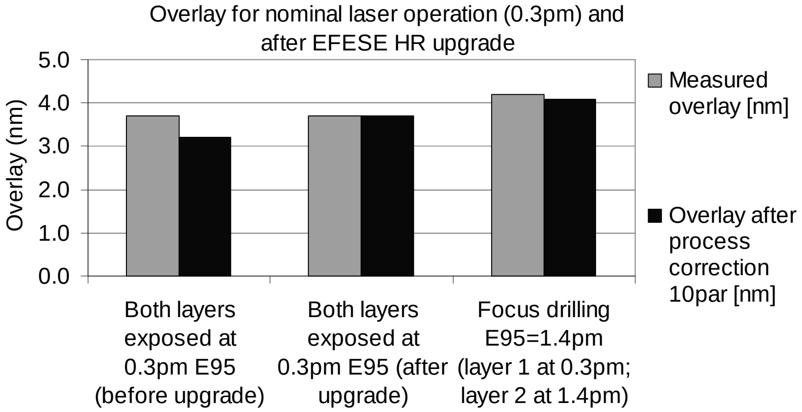


Figure 9. Overlay for nominal (0.3pm) laser operation and 1.4pm E95 focus drilling

Additional DOF data from XT:1900Gi / XLR 560i wafer exposures, using the unpolarized soft-annular illumination condition discussed previously are shown in figure 10. From this data we observe that laser focus drilling (EFESE™ HR) results in higher DOF and lower CDU compared to scan-tilt (EFESE™ Rx) across a range of focus drilling set-points. These experiments confirm our previous findings especially with regard to the CDU penalty related to scan-tilt (EFESE™ Rx) exposure.

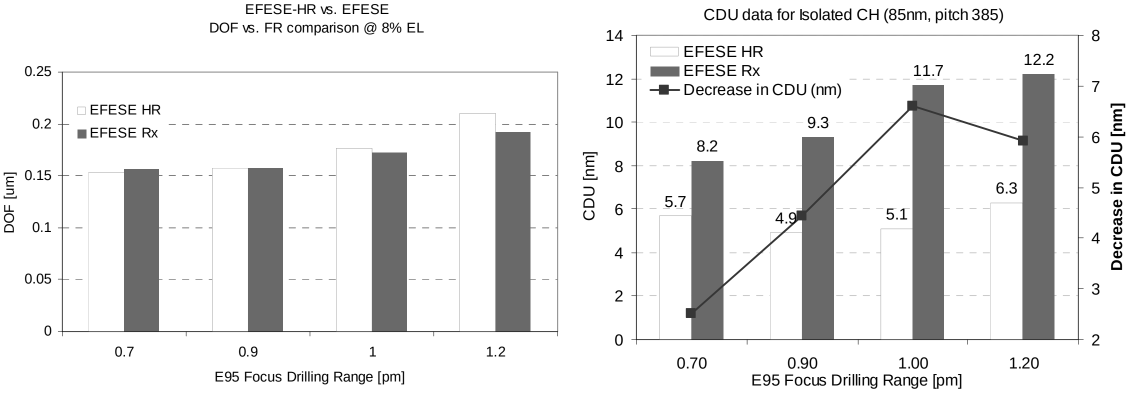


Figure 10. DOF and CDU at four laser FD (EFESE™ HR) and corresponding scan-tilt (EFESE™ Rx) settings

3.2 Optical Proximity Effects

In general the impact of laser FD on the optical proximity effect is similar to what has been reported previously as a function of changes in laser bandwidth [3,6,7,9,10] and the specific correction needs to be carried out to meet the CD targets for the desired application. In this work we investigated proximity curve changes when switching between the scan-tilt (EFESE™ Rx) and laser focus-drilling (EFESE™ HR) and we find that the behavior through-pitch for both methods can be matched to within 1nm, therefore requiring no additional change to the OPC. From data obtained at a customer site in Figure 11 we see that laser focus drilling can accurately match the scan-tilt (EFESE™ Rx) proximity behavior with maximum differences less than 1 nm, with the matching performed based on the CBW metric; this could potentially be reduced further by minor corrections to the illumination and / or focus-drilling set-point.

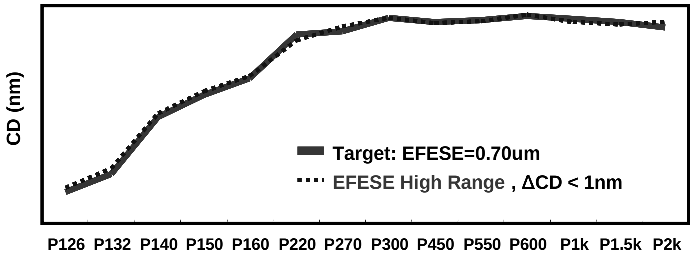


Figure 11. Proximity matching between scan-tilt (EFESE™ Rx) and laser focus drilling (EFESE™ HR)

For this example, the magnitude of the iso-dense bias (IDB) between nominal laser bandwidth and focus-drilling set-point of 1.3 pm E95 is less than 5nm, prior to correction, as shown in Figure 8. Additional data from the XT:1900Gi / XLR 560i optical-proximity matching experiments are shown in Figure 12 and confirm that proximity differences between focus drilling and scan-tilt EFESE™ Rx can be matched to less than 0.7nm using focus drilling bandwidth adjustment alone.

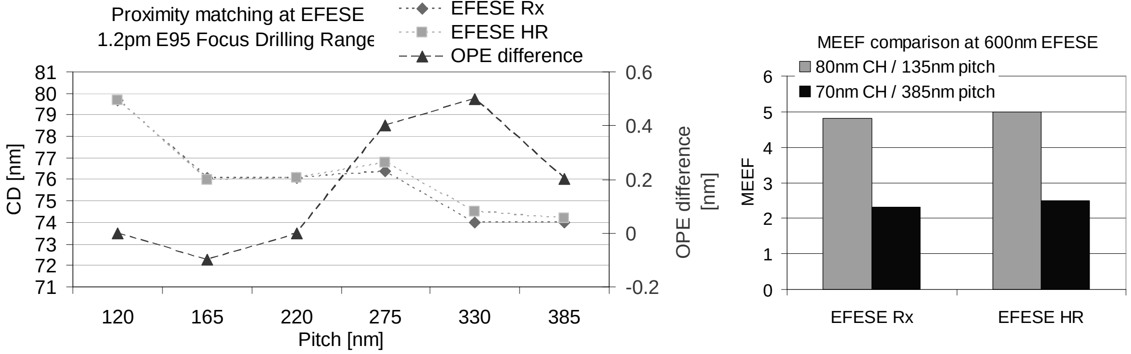


Figure 12. EFESE™ Rx and HR proximity matching (left) between and MEEF (right); XT 1900Gi wafer exposure

The plot on the right hand side of Figure 12 shows that there is no significant MEEF difference between scan-tilt at 600nm EFESE Rx setting and the equivalent laser focus drilling bandwidth of 1.2 pm E95. The change in MEEF between EFESE and laser FD is within the measurement accuracy.

3.3 Exposure Tool Stability Monitoring

In this section the results of exposure tool stability monitoring are discussed over one month of operation. A prototype laser focus drilling hardware was installed on a production tool at the customer site and performance was monitored over multiple weeks of operation. The prototype hardware did not include the new spectral metrology or feedback set-point control for focus drilling operation, discussed in section 2.2; therefore the monitoring data reflects open-loop stability performance. The data includes stability of best focus, depth of focus, image and aberration sensor performance. During the technology evaluation period, the lithography cluster was also operated in production mode with nominal light-source bandwidth operation, and stability of the system in nominal operation was equivalent to other systems of that type.

3.3.1 Best Focus Monitoring

Figure 13 shows the averaged best focus results using a customer's process wafer focus monitor collected over more than one month of system usage.

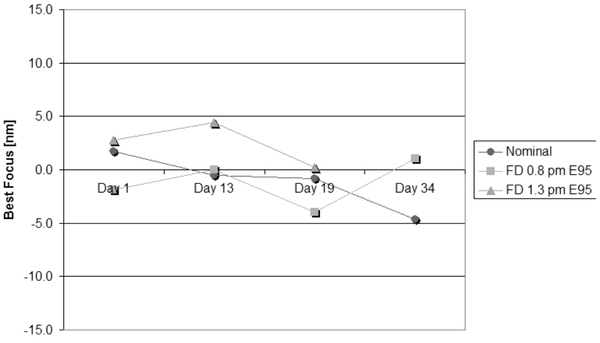


Figure 13. Best focus trend, chuck averaged

The wafer exposure uses a process-monitor mask and CD and wafer focus metrology is carried out using scatterometry. The focus stability over this period is +/- 5nm and we considered performance for two focus-drilling set-points of 0.8pm E95 and 1.3pm, which is generally within the experimental measurement noise. This performance is equivalent to variation for this process and equipment generation under nominal light-source operation as shown in Figure 13.

3.3.2. Monitoring stability of the process: Depth of Focus

The stability of the process window and DOF was also measured using the customer's Focus-Monitor test over three weeks of operation. For each monitoring data, the performance of two focus drilling set-points at 0.8 pm and 1.3 pm E95 were obtained and are compared with the nominal (non-focus-drilling) exposure. The DOF data are normalized to the baseline condition and are shown in figure 14; the data are in micrometers [μm] and represent a measurement which is highly sensitive to DOF changes. This data shows the observed increase in the DOF as detected from this wafer monitor for the two focus drilling settings and also very stable process performance over time. Again, this performance is obtained without closed-loop control for the laser focus-drilling set-point and with no compensation for spectral shape changes as discussed in sections 2.2 and 2.3. Additionally, on the right hand side in figure 14, the intra-wafer R^2 for the corresponding DOF data is reported, indicating stable across-wafer performance. It also shows that the stability at the highest focus-drilling set-point tested here (1.3 pm E95) is equivalent to nominal laser performance.

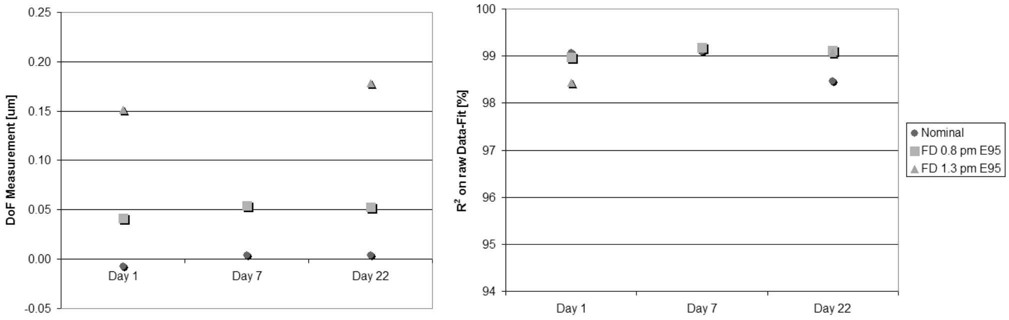
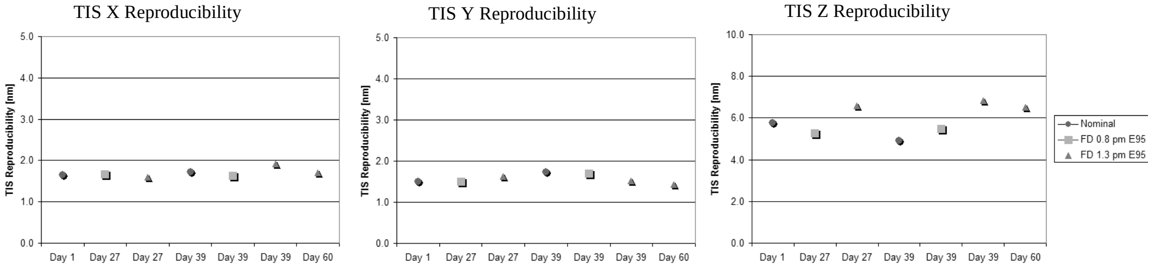


Figure 14. Normalized DoF measurement over time and R^2 from multiple points per wafer

3.3.3. Image Sensor Stability

The scanner image sensor measurement, shown in figure 15, were used to determine the image displacement errors in X, Y and Z direction and to quantify if the measurement reproducibility would be affected with the use of focus drilling. Over one month, transmission image sensor (TIS) measurements were performed on the ASML scanner at for the non-focus-drilling (nominal) condition as well as focus-drilling set-points of 0.8 and 1.3 pm E95.


TIS X Reproducibility

TIS Y Reproducibility

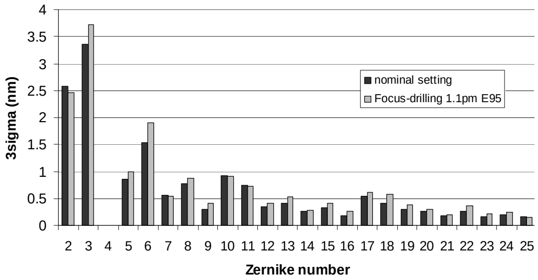
TIS Z Reproducibility

Figure 15. The maximum X, Y and Z image sensor repeatability measured by the exposure tool sensor

Although the Z data (focus) showed consistently higher reproducibility at the highest focus-drilling set-point (1.3 pm), the measured stability is very low and any changes are negligible. The same conclusion is reached for the lateral image position and the sensor reproducibility appears unaffected over the range of focus-drilling bandwidths and the period tested and reported here. Note again that the stability performance would even be expected to improve with additional closed-loop stabilization of focus-drilling set-point and compensation for spectral shape variation as determined using new spectrum metrology on the light-source as discussed in sections 2.2 and 2.3.

3.3.4. Aberration stability and repeatability

Scanner aberration sensor measurements were also carried out to determine if possible imaging or lens-manipulator changes would be observed at high levels of laser focus-drilling. It is also important to verify that the repeatability of the aberration sensor measurements do not degrade with the laser operating at high bandwidths in focus-drilling mode. The individual Zernike coefficient values (3sigma) for the Z5 through Z25 aberrations are shown in figure 16.



	nominal	1.1pm
z2-z25	1.73	1.73
z5-z25	0.90	0.99

Figure 16. Lens aberrations sensor measurement Zernike coefficients (left) and RMS data in table (right)

The average value is 0.9nm for the nominal case and 0.99nm for the high bandwidth case, which is acceptable performance. Additionally the aberration sensor measurement stability for laser focus-drilling operation is statistically equivalent to operation for nominal laser bandwidths.

IV. CONCLUSION

In his paper we present a laser focus drilling technique which has recently been developed for advanced immersion lithography scanners to increase the depth of focus and reduce process variability of contact-hole patterns. Focus drilling is enabled by operating the lithography light-source at an increased spectral bandwidth, and has been made possible by new actuators and metrology in advanced dual-chamber light-sources. We discussed wafer experimental and simulation results, demonstrating DOF increase by more than 50% with only a modest reduction in exposure latitude, contrast and CDU at best focus for 32nm logic and future technologies. Given the tradeoff engineering design, the optimum laser focus drilling set-point needs to be carefully defined to achieve the target depth of focus gain at an acceptable contrast, mask error enhancement factor and target optical proximity behavior. We show simulation results of the effects of higher-order chromatic aberration and show that image placement and critical dimension variation are minimally impacted for a range of focus drilling laser spectra. This paper points to the practical benefits of tradeoff design and co-optimization of the target focus drilling set-point and appropriately selected resolution enhancement approach to maximize the depth of focus and process-window overlap while increasing effectiveness of the source-mask solution for contact or via patterning.

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