The Flight of the scanner slit

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Process window degradation is thought to result from focus excursions introduced by lens aberrations and random variations across the wafer. But are these across-wafer variations truly random? Analysis of defocus maps reveals systematic image height, planarity, and tilt variations as the scanner's exposure slit scans across the wafer.

Focus has always been a pivotal variable for the lithographic process. Focus metrology can be difficult because of the indirect methods that typically have been employed. Our understanding of defocus and — more critically — the various effects that reduce the process depth-of-focus (DOF) is further complicated by the broad variability induced by optical, mechanical and substrate perturbations during imaging.

Several focus metrology methods exist. Commercial techniques such as line-end shortening structures (LES) and ASML FOCAL vary symmetrically about the optimum focal point and therefore require the use of a focus matrix for analysis [1, 2]. This behavior limits their usefulness for across-wafer analysis of focus uniformity. Recent LES innovations have bypassed this shortcoming by calibrating the curve against programmed focus offsets on the wafer; however, the accuracy of this method decreases inversely with the magnitude of the focus error resulting in an uncertainty approaching 50nm near best focus [3].

The phase-shift focus monitor (PSFM) employs a 90° phase feature on the reticle that results in a linear response to defocus [4]. PSFM reticle analyses measure the response of isolated features with a precision of 12nm when employed for either focus matrix or uniform across-wafer analyses. More recently, the PSFM concept was extended to an implementation on line/space gratings [5, 6]. These new structures, referred to as phase grating monitors (PGM), now replicate a shift in the pattern that, by the nature of their design, simulates the focus response of dense, periodic structures with an improved uncertainty of 6nm.

Thus, the precision and linear response of the PSFM/PGM technology to defocus provides a unique ability to analyze imaging performance over full-wafer areas where the exposure tool focus is fixed. Combining the high-precision capabilities of the PSFM/PGM test structures with the enhanced empirical data modeling of Weir PSFM software allows examination of the perturbations inflicted upon the aerial image as the reticle is scanned during product exposure.

Validation of PSFM reticle accuracy

Across-wafer focus errors are derived from both static lens aberrations and the dynamic contributions of the reticle-scan stage, wafer-stage movement, and substrate-leveling algorithms. Wafer planarity and photoresist deposition can also influence focus uniformity across the wafer through their influence on the autofocus subsystem.

To illustrate the ability of the PSFM reticle to resolve small errors in focus, an oxide wafer was exposed using a commercial 193nm scanner at nominal focus and a dose of 25mJ. The numerical aperture was set to 0.75 with $\sigma = 0.7$. Three fields on this wafer were separately programmed with deliberate offsets in focus of ±70nm as shown in Fig. 1. The graph shows image defocus as a function of the Cartesian "X" or horizontal location on the wafer,

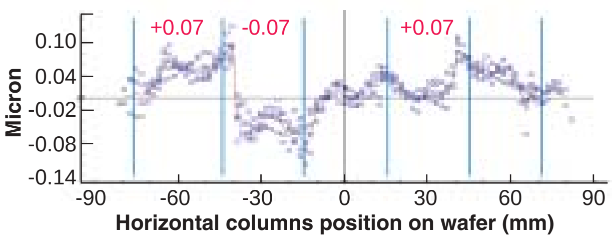

Figure 1. Plot of focus error vs. position on the wafer for programmed fields, showing the ±70nm programmed offset as well as edge-induced tilt.

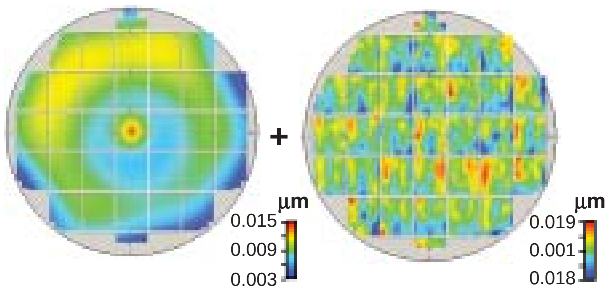

Figure 2. Weir PSFM modeled mean defocus shows a) a wafer-scale variation. b) A field-by-field defocus variation becomes visible when the wafer contributions are removed.

within the seven die of one row. Since we are looking for focal plane variations, the mean field, or focus signature of the lens, was removed by the Weir PSFM software for clarity. Figure 1 clearly shows the 70nm step induced by the programmed offset. Notice also the induced tilt of the field in the second die from the right side of the wafer (i.e., the last full die before the wafer edge). Typical scanner autofocus systems tend to exhibit tilt near a wafer's edge, illustrating that image scans are not uniform across the wafer. The errors also suggest caution for focus metrology techniques that depend upon programmed focus offsets for real-time calibration [2].

Deriving scan-slit flight phenomenon

During an exposure sequence, the reticle is scanned across the horizontal lens-slit aperture, matching travel direction and velocity with that of the wafer to register the reticle's image to the previous process step. From the reference frame of the wafer, the slit appears to glide "up" or "down" across each exposure-field; each scan thereby exhibits the flight characteristics of pitch, yaw, and roll similar to those seen by an airplane.

The static contributions of the exposure aberrations and those of the wafer must be removed to resolve the flight stability of the slit. Both wafer-scale and field-scale phenomena are derived from location or spatial modeling by Weir PSFM using the raw-defocus data from the PSFM reticle. Figure 2a shows the modeled influence of wafer bow and photoresist planarity. The total substrate-induced variation ranges over 12.3nm, most defocus being contributed by the radial ring replicating the photoresist deposition pattern. Wafer tilt and bow, relatively small in this instance, can be a significant contributor to the loss of DOF when ultraflat substrates are not used. Wafer tilt is separately corrected from the field tilt during scanner setup. Weir's removal of the wafer-induced errors results in a clear evaluation of the field-contributed defocus, as seen in Fig. 2b.

Since the objective is to observe variations in lens and reticle-scan defocus, the software must calculate and remove the static components of each. The physical construction of the scanner embodies a horizontal lens slit with aberrations repeated along each row of the exposure. Similarly, the up and down travel path of the reticle scan stage is replicated along each column of the field. Separate defocus signatures are derived to characterize the conjugate defocus plane of these stable lens-slit and reticle-scan aberrations. Weir PSFM automatically models each signature by averaging every field's contribution across the wafer. This constitutes the static contribution of the lens and scanning system to image defocus.

Finally, the static wafer, lens-slit, and reticle-scan signatures are removed from each field to visualize the "flight path" of the slit during the exposure-scan. The resulting measured mean-focus variation is shown as a wafer contour plot in Fig. 3. Recall that the slit scans either up or down each field during exposure; the scan direction of each exposure has been identified by the white arrows.

Flight-path analysis

Induced, dynamic image-plane bow and tilt — as much as 85nm — can be seen in the fields in Fig. 3. These perturbations reflect the focus variations induced by the scan nonuniformity of the reticle. The wafer edges typically exhibit enhanced focus errors that are particularly pronounced on the left and right sides.

The two highlighted rows on this wafer contain fields with a single scan direction for the slit. Comparing these two rows highlights disparate behavior. Focus across the slit is uniform for most of the down scan-direction exposures, dipping slightly only at the end of travel. The up scan direction displays two interesting characteristics. First, the fields exhibit a defining tilt with the left side raised relative to the right. This tilt can be quantified by the tilt coefficient of the model, and perhaps removed by setting the exposure tool differently for up and down scans. Second, the curvature of the slit seems to change with some of the scans as in the center field of the up scan row. Let's consider the potential sources of this induced bow.

Localized focus changes can be associated with wafer backside contaminants, but that does not seem to be the case here. This curvature change seems to be associated with

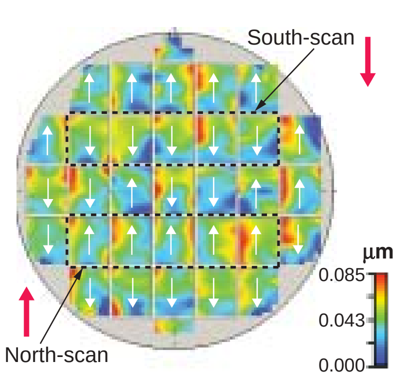

Figure 3. Exposure-slit flight characteristics depend on scan direction and edge proximity. Removing the wafer perturbations as well as the slit signature results in a defocus contour path for each field exposure.

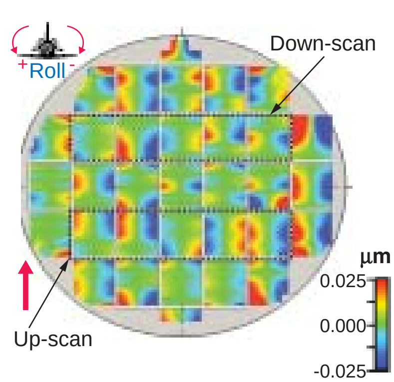

Figure 4. Across-slit focus or "roll" of the slit during exposure. Similar to the flight of an airplane, the slit will tilt or roll depending upon its direction of scan and proximity to the wafer's edge.

flexing of the reticle during a portion of the scan. Similar to a wing in flight, the reticle flexes slightly due to stresses during travel. The approximate variation of 25–35 nm of flex is consistent with observations of exposure tools from all scanner vendors. The PSFM reticle was not pellicle-protected and flexure may be amplified even more when reticles employ such extrinsic devices.

Examination of the across-slit tilt coefficient for the individual fields in Fig. 4 illustrates the similarity of slit and wing travel. Here the "roll" (where the defocus has opposite signs on opposite sides of the slit) and its sensitivity to scan direction are apparent. Even more strongly seen is the tendency of the slit to bank to the right on the right side of the wafer. These dynamic responses can significantly affect the process DOF consumed by the exposure tool, this example exhibiting a 50nm defocus range for the three fields at the right edge of the wafer.

More complex analyses can reveal the across-slit lens focus signature and its variations due to wafer-edge effects as well as rough spots in the stage motion and the tendency of the image to climb away from the wafer plane or descend into it along the scan direction, among other things.

Conclusion

The process DOF is significantly eroded by the mechanical elements of exposure-tool slit scanning. Wafer-stage and reticle-scan induced errors can only be fully analyzed using a focus monitor and full wafer exposure of fields conducted with a fixed exposure-tool focus. Applying advanced models to the focus data gathered from the wafer expands our ability to determine the finer contributions of wafer planarity and slit travel during exposure. With nominal DOF now approaching 200nm for some processes, the 85nm of turbulence shown here becomes significant. ■

Acknowledgments

FOCAL is a registered trademark of ASML, and Weir PSFM is a trademark of TEA Systems Inc.

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