Multi-phase photomasks as in-situ monitors for image-forming optical systems

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The semiconductor industry relies on continuous improvements in the resolution of optical lithography systems to increase the functionality of the microchips it makes. As the minimum dimensions of semiconductor manufacturing processes have shrunk to nanometer scale, imaging defects created by flaws in lithography systems have become much more significant. This has made it important to develop techniques to monitor such flaws in situ. Five new ways to do so have emerged from advances in multi-phase photomask technology. These techniques use principles that could apply to other fields of optics.

A projection printing tool, commonly referred to as a stepper or scanner, is a complex system of optical elements, represented in a simplified diagram in Figure 1(a). A coherent and linearly polarized laser source is scrambled in an optimal way by the illuminator and condenser optics. The light then scatters off the photomask and is captured by the projection optics, which shrink the image of the mask onto the wafer. This image is recorded in a chemical substance called a photoresist, which becomes soluble when it has been exposed to enough photons. Subsequent steps transfer the pattern into an underlying layer. Multiple iterations of this process help create the complex circuitry of a modern computer chip.

The photomask has evolved from a simple chrome-on-quartz stencil to more complex structures such as the phase-shift mask (PSM), to improve the resolution and robustness of the lithography system. In a PSM, selective etches into the quartz substrate improve imaging by manipulating the scattered wavefront. The monitors described in this article extend this approach, by combining patterns in the chrome with multiple phase-etched regions. This produces a wavefront that creates an image-plane response that is only sensitive to the desired optical effect. Data is then collected from the images formed in the photoresist. A sample of the topography of a cutline through a mask using this technique is shown in Figure 1(b). The colors show how much the quartz has been etched and thus, the phase shift of the local wavefront.

Illumination monitors: The first two monitors, the linear-phase grating (LPG) and linear-phase ring (LPR), both help characterize the angular distribution and uniformity of an illumination source. The LPG shown in Figure 2(a) has four successive phase-shift regions, etched in stripes in a chromeless mask. This only diffracts incident light into the +1 and higher diffraction orders, at an angle determined by the period of the grating. The pupil of the projection lens is then used as an aperture to clip a certain portion of the illuminator. The total intensity of this portion is recorded in photoresist. Putting multiple LPGs on a mask provides a quick way to compare intensity in various parts of the illuminator.

The LPR shown in Figure 2(b) does a similar thing in a different way. A circular pattern resembling the point-spread function, combined with a four-phase linear grating, creates a central image intensity that depends on a single illumination

Figure 1. (a) A simplified projection printing tool. 1: The illuminator. 2: The condenser optics. 3: The photomask. 4: The projection optics. 5: The wafer. (b) Sample profile of a phase-shift-mask monitor, corresponding to the cut-line drawn in the mask design.

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monitoring method

Aberration monitors: The pattern-and-probe aberration-monitoring method uses an interferometric reference probe surrounded by an open geometry of varying phase. This geometry corresponds to the inverse Fourier transform of the aberration of interest, when expressed as a Zernike polynomial. The probe interacts with the coherent spillover from the surrounding pattern and changes intensity linearly with the amount of the Zernike aberration of interest. This technique has measured defocus aberration down to 0.01 waves rms. Sample designs are shown in Figure 2(d) for the defocus and astigmatism aberrations.

Polarization monitors: Polarization is becoming important in lithography systems because of the uptake of ultra-high numerical aperture (NA) space optics. At such high NAs, the system’s ability to create an image is severely dependent on the polarization of the illuminator. The PSM polarimeters use a side effect of high-NA imaging to create a central image intensity that depends on the polarization state of the illuminator. The two patterns of Figure 2(c) enable the intensity of orthogonal polarization components (shown by the arrows) to be compared. With multiple patterns it is possible to measure the Stokes parameters of the system, which completely characterizes its polarization state.

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PSM monitors: The last class of patterns is designed to self-test the effective phase of the shifted regions of a PSM, to ensure it has been made properly. The patterns use an interferometric reference probe but the change in image intensity (relative to a nearby isolated probe) is due to phase-etch errors in the surrounding geometry. To our knowledge, this is the most sensitive image-plane measurement technique for certain feature sizes of interest.

These five types of phase-shift monitor offer novel ways to ensure that lithography tools work properly, so ensuring the continued progress of the semiconductor industry. Although the concepts have been developed for optical lithography, we hope they will be useful in other fields of optics.

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References


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