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Freeform DOEs Extend Optical Lithography

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By improving the aerial image slope and reducing CD error freeform DOEs in an SMO system can reach higher NILS fidelity.

Source mask optimization (SMO) has been identified by industry leaders as the only practical method to reach the 22nm node. [1] To fully realize the potential of SMO, next-generation source definition optics must create exceedingly precise freeform pupils, be consistent in volume and not deviate from expectations. Tessera's DigitalOptics™ diffractive optical elements (DOEs) are ideal for these requirements and essential to prolonging the life of optical lithography.

Optical Lithography Must Soldier On

The delayed release of extreme ultra-violet (EUV) lithography production tools requires 193nm optical lithography to be extended to meet the next generation of lithography nodes. As critical dimensions shrink to nearly an order of magnitude less than the source wavelength, lithographers must use all resolution enhancement techniques at their disposal. Techniques that were originally considered too complicated and costly to become mainstream are now regarded as primary enablers to extend the reach of optical lithography. These tools include immersion lithography, double patterning technology and, most recently, source mask optimization.

Resolution enhancement technologies such as optical proximity correction and phase-shifted masks are quite mature. But the amount of enhancement that can be included is limited by the overall information content of the mask. Normalized image log-slope (NILS) is generally used as a measure of the information content in the aerial image. A larger value of NILS can be interpreted as more information at the proper position of a feature edge. [2]

SMO can substantially increase the NILS "bandwidth" by using pixelated structures in the mask. As a result, the data contained within the mask no longer resembles the desired printed circuit. With the increased freedom afforded by SMO, the mask is optimized in tandem with a pixelated freeform pupil and significant resolution enhancement is achieved. The extent of this enhancement is greater than by optimizing the mask or pupil alone.

The full potential of the SMO technique can only be realized by the use of freeform pupils that can be created by diffractive optical elements.

DOE Source Definition Precision

Historically, movable aperture blades have been used to shape the pupil in a scanner. This approach functions as an aperture stop -- improving depth of focus by sacrificing optical transmission. Instead of blocking the undesired sections of the pupil, DOEs redirect most of the illumination into the desired pupil map locations. DOEs can effectively propagate approximately 75% to 85% of the illumination source. The result of this efficiency improvement is increased process latitude and tool throughput.

DOEs were first used to replace common blade pupils that were composed of wedge or circular pole shapes of uniform intensity. But DOEs can also create arbitrary freeform pupil shapes. Some examples of freeform pupils consistent with SMO requirements are shown in Figure 1. These designs from Mentor Graphics Corporation illustrate structures that cannot be physically realized by aperture blades due to their grey-tone intensity variations. To demonstrate the freeform concept, these designs were fabricated into DOEs by Tessera.

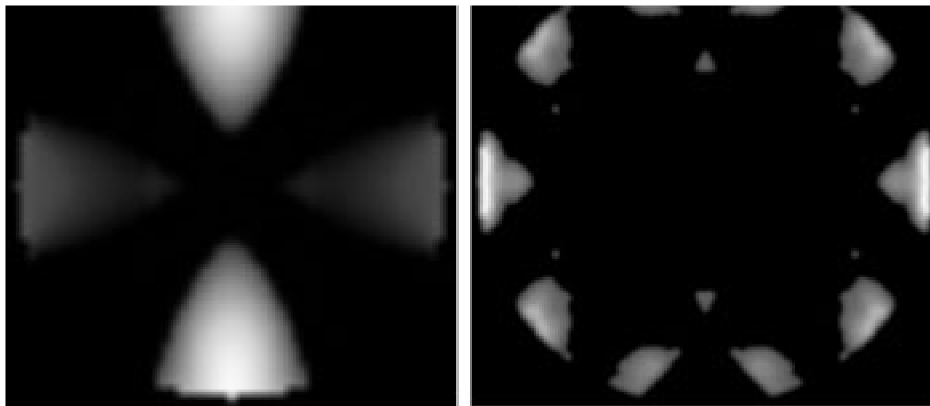

Figure 1: Examples of freeform pupil illuminations for semiconductor lithographic systems. (Design parameters courtesy of Mentor Graphics Corporation.)

An off-axis illumination pupil map as shown in Figure 1 is used to specify the DOE design. The pixel density of freeform pupil maps are typically in the range of >104 pixels with individual pixels < 0.01 sigma [3], which is the same density and spacing provided by standard library DOEs. The spatial density is not the limiting factor in pupil fidelity, as the scanner’s illumination divergence will smooth and blur adjacent pixels.

The DOE itself is an optically transmissive quartz plate that is encoded with the specified pupil function. The physics are similar to holography, but instead of optically interfering wave fronts to record a hologram into film, computed optical wave fronts are directly transferred into a transmissive plate by means of standard lithographic techniques. The resulting DOE phase contours contain a

distribution of diffractive gratings that direct the incident illumination upon the substrate into the specified pupil shape. While the DOE is largely a-periodic, it does contain a range of proper spatial frequencies within a finite length or pseudo-period.

This pseudo-period can be described by a form of the grating equation:
d = m• / sin •

Where d is the grating period, m is the integer-valued desired diffraction order from the grating, • is the wavelength of the illumination and • is the angle at which the desired order is deflected. The separation between diffraction orders is linear in sin • or numerical aperture (NA), assuming an fsin • lens. The extent of the NA provided by Tessera DOEs is consistent with the sigma requirements of current lithography tools.

Accordingly, the spacing between adjacent orders is governed by the case of m=1:

Order pitch = sin •m=1 = •/d

It should be emphasized that the physics of the DOE's grating equation imparts consistency and precision into the pupil result. The overall NA will remain constant and the location of the diffraction orders will be exceedingly repeatable from part to part. For an inconsistency to occur, the illumination wavelength and/or the overall DOE period size would have to deviate from specification, both scenarios are extremely unlikely.

DOE Consistency

Several critical performance parameters of a DOE can vary during the fabrication process. These include intensity uniformity, residual zero order and stray light. Tessera utilizes stepper-based lithography for diffractive element fabrication. Starting with an E-Beam generated mask set, a DOE is fabricated by sequentially aligning, exposing, developing and etching successive pattern layers into an excimer-compatible substrate. [4] One of the primary advantages of this approach is process repeatability. Since the diffractive design and fabrication approach in the example is based on discretely quantized levels with lithographically defined features, the optical result is extremely consistent.

The ability of the DOE's performance to match the pupil map specification will become more important as 193nm lithography is extended. To validate our design capability with next generation grey-tone pupil maps, we created a challenging test pattern, shown in Figure 2. We then explored our ability to match the design parameters and the repeatability of the manufactured result. [5]

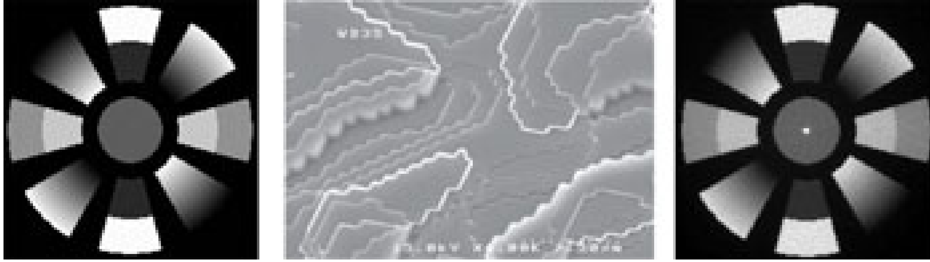

Figure 2: (left) Grey-tone freeform test pattern specification. (center) SEM image of a portion of the fabricated DOE. (right) Optical result of the manufactured DOE.

One byproduct of manufacturing is the central bright spot “zero order” as depicted in rightmost image in Figure 2. This effect can be caused by process variations of the grating structures within the DOE. Any amount of zero order intensity will be obvious in a cross-sectional plot, however the relative power contained within this one diffraction order versus the power within the area of the pupil poles is typically very small (<1%). The zero order can be reduced by process adjustments during the DOE fabrication. The examples presented within these test cases were not optimized for zero order.

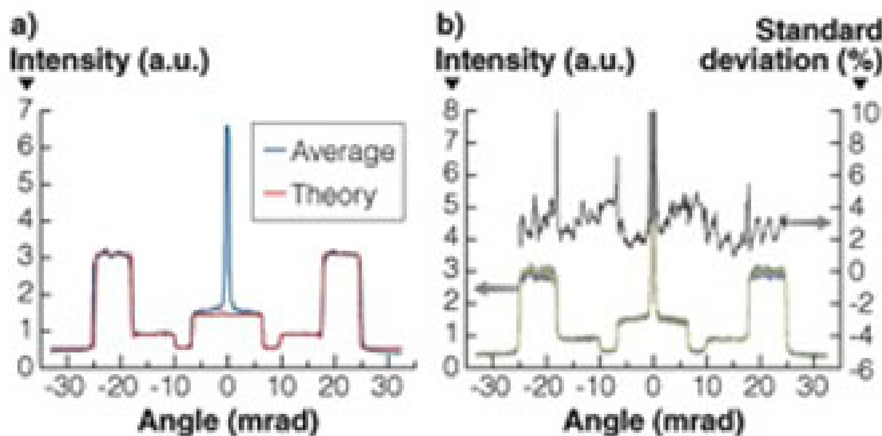

Figure 3: (a) Average intensity cross-section for a DOE corresponding to the freeform pupil map of Figure 2, with (pink) theoretical predictions and (blue) measured values for the manufactured DOE. (b) Average pupil intensity cross-sections of 20 manufactured DOEs corresponding to the freeform pupil map of

Figure 2. The upper trace is the standard deviation per pixel.

The average pupil intensity cross-sections from 20 manufactured DOEs (Figure 3) demonstrate how well the Tessera process can generate multiple intensity level targets within the same DOE design. [6] For the discrete intensity levels in this pupil map, we found that the worst case deviation from the design was 6.2% with an average deviation from target of 1.85%. The uniformity within a zone was found to be within ±4%. Similarly, the average difference between measured and target for the sloped regions was 4.7% with a maximum deviation of 7%.

Equally important is part-to-part repeatability. Figure 3b shows the DOE output-intensity cross-sections for 20 manufactured units and their standard deviation per pixel. For this complex example, the average standard deviation is 4%, showing quite good repeatability. Figure 3b also illustrates the repeatability of the inner and outer sigma for the various zones or poles. Note that the edge transitions for all 20 samples line up perfectly, which is due to the physics of the grating equation.

SMO sensitivity to manufactured DOE performance
Coskun et. al explored what effect any Tessera DOE manufacturing deviations would have upon the performance of an SMO system model. [7] An SMO design case was optimized by Cadence Design Systems for randomly placed 32nm contact holes. A pupil was used for this study. The corresponding DOE was encoded, fabricated and tested by Tessera's manufacturing facilities. The measured fabricated result from the DOE was absence of any discernable zero order. The specified and measured pupils have an root mean square (RMS) difference of 0.59% and a maximum peak difference of 1.24%.

The metrology data was input by Cadence Design Systems into their SMO system model and the effect upon the process window was determined. The fabricated DOE caused the SMO system performance to deviate from ideal by 8nm in depth of focus (DOF) and less than 1% in exposure latitude (EL) from best focus. This provided process window improvements of more than 50% in exposure latitude and approximately 30% in DOF compared to the best standard pupil as shown in Figure 4.

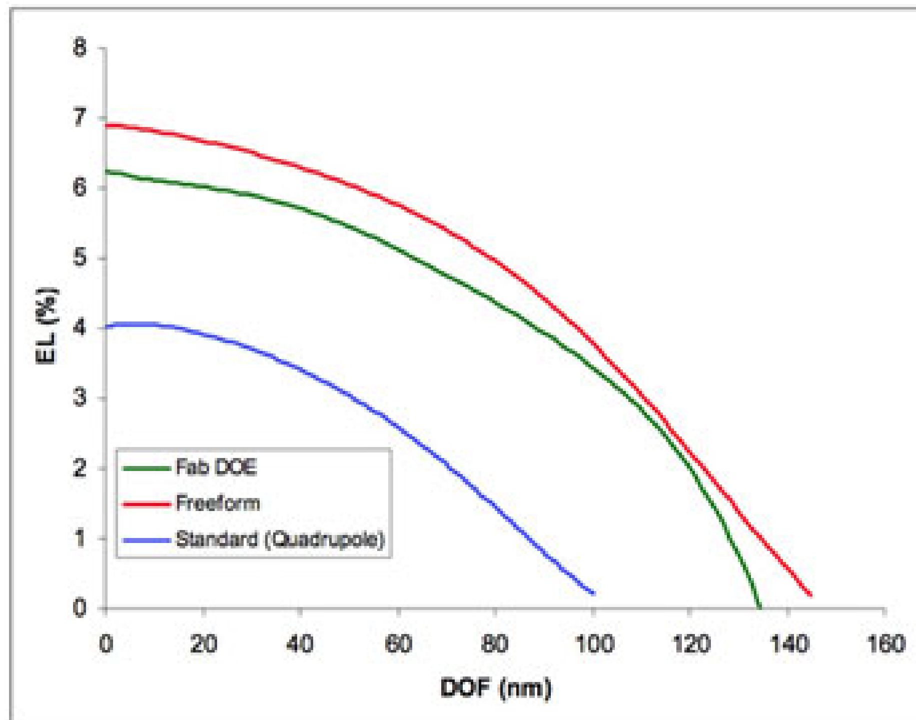

Figure 4: (red) Process windows associated with a random 32nm contact hole design study comparing the Freeform design specified by SMO, (green) the fabricated DOE pupil performance, (blue) and the best standard library pupil. Image courtesy of Cadence Design Systems.

The process improvement over the standard pupil outweighs any deviations from specification. At the 3.5% EL location, the depth of focus is 40nm for standard illumination versus 100nm for the fabricated DOE illumination. This is an improvement of 150% in DOF for the same exposure latitude.

The result is that freeform DOEs in an SMO system can significantly achieve higher NILS fidelity by improving the aerial image slope and reducing CD error. In the specific case of the 32nm contact hole model, NILS was the same or improved at all random hole locations, with the largest improvement at the location with the lowest NILS associated with standard illumination.

Summary

For over the past decade, diffractive optical elements using DigtialOptics™ technologies from Tessera have played a vital role in enabling lithography tools to continue to advance Moore's Law. While EUV has been delayed, optical lithography must continue. EDA houses such as Mentor Graphics and Cadence Design Systems have detailed that there is a critical need for freeform DOEs in support of SMO. [6][7]

To validate the requirements for this next-generation technology, freeform DOEs have been encoded, manufactured, measured and tested in simulation and lithography tools. The resulting image enhancement and its effects upon exposure latitude, depth of focus and NILS have been detailed and proven, even when manufacturing tolerances are taken into account.

While freeform pupils required for SMO are exceedingly complex and rigorously demanding, they can be physically realized by DOE technology. Moreover, next generation DOEs will be as proven and reliable as the standard library and custom DOEs that are in present day scanner lithography tools.

References

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