Numerical resolution enhancement in mask-aligner lithography

Ulrich Hofmann, Nezih Ünal, Ralph Zoberbier, and Kristian Motzek

Simulation-based techniques extend the limits of lithography for applications that benefit from the cost advantage of mask aligners and their capability to print on large and non-planar substrates.

Mask aligners are commonly used tools in photolithography, a microfabrication process used to transfer a pattern from a mask onto a substrate. They work by letting light pass through the mask in areas without an absorber coating, exposing a photore sist on the substrate. Because their resolution is limited to a few micrometers, they are regarded as tools for ‘non-critical’ applications. However, they are low cost and provide the capability to print on large and non-planar substrates, which motivates the development of simulation-based resolution-enhancement techniques (RETs) to enable the fabrication of next-generation products using mask aligners.

Computational lithography approaches, such as source-mask optimization (SMO), are used in advanced integrated-circuit manufacturing to increase lithography resolution. SMO simulates how a pattern would print on the substrate, allowing users to modify the mask layout (using a technique called optical proximity correction, or OPC) and modulate the shape of the light source in conjunction. The LAB lithography-simulation software we introduced a few years ago,\(^1\) enables the application of these RETs to extend the uses of mask-aligner lithography. OPC allows, for example, the manufacturing of very high resolution color displays for smartphones.

Simulating mask-aligner lithography requires the computation of the light intensity below the mask using an algorithm based on the Fresnel diffraction model. The difference to projection systems (where a lens is placed between the mask and the substrate) is that, due to the small proximity gap of a few microns to up to a few hundred microns, lithography simulation needs to take many diffraction orders into account. On top of this, it is necessary to include multiple wavelengths in the simulation (due to the typical broadband spectrum), each one having a finite peak width and distribution and on much larger areas than CMOS simulation typically requires.

Our lithography-simulation software enables fast, accurate calculation of the intensity image for all mask-aligner exposure tools. Further, we recently improved our software to model the capability of SUSS MicroTec mask aligners that allow

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modulation of the source shape through an exposure-optics technique. With these improvements, the software enables SMO, meaning the user is capable of optimizing source shapes and mask layouts for specific applications to improve resolution and depth of focus.²

The software calculates the so-called aerial image—the light intensities in the air (no resist, no substrate) at a given distance below the mask—based on Kirchhoff’s scalar-diffraction theory. The model takes into account a broadband light source (such as the spectrum of a mercury lamp) and the source shape (circular with collimation angle, arbitrary, loaded from a database of measured mask aligner source shapes or custom designed). The software then propagates the aerial image into the resist, taking into account all back-reflections from substrate and coatings. Using the Dill Model,³ LAB software then computes the concentration of photoactive compounds from the light intensities, while the development process is simulated using empirical models such as MACK4.⁴ Since the resist models are empirical, users need to calibrate the model parameters to the experimental data, from a development rate monitor or a contrast curve, for example. An automated resist-parameter-calibration utility is included in the software.

The time for simulating the full 3D intensity image for a typical area of 100\(\mu\text{m}\times100\mu\text{m}\) is short enough that users can do hundreds of simulations with varying conditions (gaps, source shapes, mask layouts and others) in a few hours. Since the intensity image already contains most of the information on how the structure will print, it is the main indicator for optimizing mask layout, source shape, gap and dose variation. The example in Figure 1 demonstrates the effect of OPC by optimizing the mask layout using simulations.

Figure 2 shows another example of creative use for mask aligners, demonstrating the benefits of adjusting the angular spectrum of the illumination. In this case, the mask serves as a Fresnel lens, projecting the image of the angular spectrum onto the substrate, which results in significant depth of focus. The manufactured structures, shown on the right, approximate to the desired square geometry very well.⁵

A first step in validating printability is to look at the intensity image (see Figure 1). To find out the optimal print conditions for a given layout, The software makes 2D image views available, as well as their 1D cross sections, matrix views, overlay views and quantitative predictions such as intensity values, slopes and log-slopes at all positions in the layout. For example, users can derive the line-width sensitivity to gap and collimation angle, allowing them to generate specs on how accurate the proximity gap needs to be set.

Lithography simulation enables the extension of mask-aligner technology beyond the classical limits through resolution-enhancement techniques such as layout optimization, source shaping, advanced mask technologies (grey-tone, phase shift) or combinations thereof, such as in SMO. In the future, we will continue to enhance our software in close cooperation with users to enable new applications. Our current developments will allow users to simulate complex 3D topographical stacks for advanced 3D packaging, MEMS, and other applications.

Figure 2. Source-mask optimization example for large gap (800\(\mu\text{m}\)) proximity printing. Source: Toppan Photomask and SUSS MicroTec.
Author Information

Ulrich Hofmann and Nezih Ünal
GenISys GmbH
Taufkirchen, Germany

Ralph Zoberbier
SUSS MicroTec
Garching, Germany

Kristian Motzek
Fraunhofer Institute for Integrated Systems and Device Technology (IISB)
Erlangen, Germany

References