157nm Lithography - Window of Opportunity

Harry Sewell, James McClay, Peter Jenkins, Bruce Tirri, Donis Flagello, and Jan Mulkens

This keynote paper looks at the window of opportunity for 157nm lithography. The issues and challenges of the new 157nm lithography are identified and reviewed in the context of optical scanning system development. Major developments associated with the solution to problems are detailed: Optical material development; birefringence of optical materials; convergence of optics designs; contamination purging; and 157nm laser illumination. Micrascan VII and AT systems are highlighted.

Resolution performance is projected against the Semiconductor Industry Association Roadmap. Both measured data as well as predictions of system performance are given. The window of opportunity for 157nm lithography is confirmed.

Keywords: 157nm lithography; 65nm node; 50nm node; birefringence.

1. Introduction

Optical lithography is the production technology for the fabrication of integrated circuits. Semiconductor industry roadmaps require optical lithography to deliver resolution improvements every year (Figure 1). This improvement has been achieved by steady increases in the numerical aperture of the imaging optics, the shortening of the exposure wavelength, and the introduction of advanced imaging techniques such as off-axis illumination and phase-shifting masks (Figure 2).

Currently 248nm (DUV) wavelength illumination is used for the production of these advanced semiconductor devices: microprocessors, memory chips, application specific integrated circuits (ASICs). The next wavelength, 193nm, is in full development and is nearing introduction for production at the 100nm node. It is expected that 193nm optical lithography will embrace the 70nm node using extremely high numerical apertures, but it is not expected that 193nm lithography can be stretched to provide 50nm node lithography in production.
EUV optical lithography (13nm wavelength) is in development, but it requires a vacuum system and significant developments in engineering and technology. Progress is marked, but EUV lithography is still estimated to be at least six years away from application to production. In the semiconductor industry roadmap, there is a window of opportunity for optical lithography at the 157nm wavelength. This window begins with the 70nm node, covers the 50nm node, and will be extended toward the 35nm node where it overlaps with the EUV lithography.

Semiconductor equipment manufacturers have responded to the need to fill the technology gap between 193nm lithography and EUV lithography by rapidly developing the engineering for the 157nm wavelength.

2. 157nm Optical Exposure Tool Challenges.

Engineering studies have been completed on the key aspects of 157nm optical lithography. Many engineering challenges have been overcome; progress has been steady and success realized. This paper discusses progress in: optical materials; optical material processing; intrinsic birefringence; optical coatings; environmental and contamination control; and optical designs. Expected imagery performance is reviewed, as is the expected resist performance. Engineering is being confirmed using the 157nm development system (Figure 3).

2.1 Optical Materials

For the 157nm wavelength, the number of optical materials available for optics manufacturing is very limited. Significant focus has been on calcium fluoride, and some attention given to other fluorides such as barium fluoride. Considerable progress in the full-scale manufacture of calcium fluoride has been achieved by companies such as Schott, Corning, ACT, STC, and Bicron. The quality of calcium fluoride in large ingot form has steadily improved. Figure 4 shows the homogeneity of a calcium fluoride optical blank that is to be used for a large prism element.

![Homogeneity data for Calcium Fluoride optical blanks](Figure 4)

This is the homogeneity map for prism block during manufacture. It was still oversized at this point. Note that the 37 term removed residual of 0.01 is comparable to a similar fused silica prism.

Figure 5 shows the improvement in homogeneity for calcium fluoride lens material (four Zernike terms removed).

![Calcium Fluoride Lens Material Trends](Figure 5)

This high quality of calcium fluoride supports the building of large optical elements such as beam-splitter prisms for use at 157nm wavelength. Calcium fluoride material has been grown and cut to give optical-quality large-lens blanks and beam-splitter cube halves. Figure 6 shows such a beam-splitter element in manufacture.
The optical quality of a crystalline material is measured not just in terms of refractive index homogeneity but also birefringence. Birefringence is a measure of the difference between refractive indices along two axes (often called a “fast axis” and a “slow axis”). An improvement in stress birefringence values now allows large elements such as beam splitter halves to be produced. Stress birefringence values after annealing are now at or near the 1nm/cm specification value for <111> material.

Stress birefringence is just one form of birefringence. Recently, intrinsic birefringence was identified (4) as an issue with calcium fluoride, particularly at a 157nm wavelength.

2.2 Intrinsic Birefringence

Intrinsic birefringence, unlike stress birefringence, is fixed in the crystal. It is not possible to change or reduce its magnitude. It is intrinsic to the calcium-fluoride cubic lattice. About a year ago, the realization of this issue presented a major problem for 157nm lithography. Since then, much has been done to accurately measure the magnitude of the intrinsic birefringence and to engineer ways to reduce its optical effects. Intrinsic birefringence is shown in Figure 7 on a polar contour plot.

A polar contour plot of intrinsic birefringence shows the difference between the refractive index of the fast axis and the slow axis, plotted in polar coordinates for beam angles into the crystal. The center of the polar contour plot is the optical ray direction normal to the <111> crystal face. The plot indicates that a ray of light that is normal to the <111> direction passes through the crystal without birefringence, but if the ray of light is not normal but is tilted to an angle of 30°, then there will be three polar directions at which the beam experiences maximum birefringence. Polarized light will be split by the birefringence. This produces image aberration effects that reduce image contrast and increase scattered light. The production of good optics requires that this intrinsic birefringence effect be corrected for in the optical design.

The crystal orientation of the material in the lens becomes very important; <111> oriented material has a smaller birefringence free angular window than <100> oriented material. <111> orientation has a threefold birefringence symmetry. <100> has a fourfold birefringence symmetry. See Figure 7.

Optical designers have developed combinations of crystal axis orientations that almost completely eliminate the effects of intrinsic birefringence in lens groups. Figure 8 shows how a combination of pairs of optical elements made with two crystal orientations <100> and <111> can be used to nearly completely cancel the effects of intrinsic birefringence.
The use of experimental setups such as that shown in Figure 9 demonstrates that a pair of <111> lens elements, with one element rotated 60° with respect to the other, will produce spherically symmetrical positive birefringence.

It is also shown that a pair of <100> lens elements, with one element rotated 45° with respect to the other, will produce spherically symmetrical birefringence of the opposite sign to the <111> material. By adjusting the thickness of the <100> elements with respect to the <111> elements the effect of birefringence can be almost completely eliminated.

The revamping of optical designs to accommodate intrinsic birefringence has caused some delays in 157nm programs. Software currently only traces one refractive index. Current software does not account for ray splitting caused by the refractive index differences resulting from birefringence. This issue is being addressed. Optical design programs, e.g., Code V, have been upgraded to address the design requirements.

2.3 Optical Material Processing

Progress has been made in the polishing and finishing of calcium fluoride for optical elements.

Polishing processes for calcium fluoride have been developed to give surface-finish results as good as are obtained when using quartz. Figure 10 shows surface-finish results for a calcium-fluoride lens element. Surface-finish values are now typically <0.0001 for individual Zernikes. Finishing is now being accomplished using magneto MRF polishing systems under computer control.

Figure 11 shows a typical arrangement for computer-controlled polishing.

Figure 12 indicates a typical polishing sequence; it results in a surface finish better than 2nm (rms). Lens elements are being completed with optical coatings that have been specially developed for the 157nm wavelength.
2.4 Optical Coatings

Coatings are integral to any optical system. Early concerns about the durability of coatings have largely been allayed. Coatings now meet the required life expectancy (Figure 13), but only if very careful control of the ambient atmosphere is achieved - particularly for hydrocarbon contamination.

2.5 Environmental and Contamination Controls.

Controlling hydrocarbons in the system is vital to prevent the degradation of optical surfaces. The elimination of oxygen and water vapor is necessary because they absorb 157nm radiation. The engineering work has developed strict specifications with regard to acceptable concentrations (in parts per billion) of hydrocarbons, organics, oxygen and water vapor at specified positions in the optical train and in the system components. It has been found, though, that some oxygen is beneficial. It cleans the optical elements. Small quantities of oxygen are, therefore, introduced to clean and keep clean the optical systems. Figure 14 shows the results of organic contamination (toluene) and 157nm radiation on a lens element.

![Figure 12. MRF Polishing Example - Calcium Fluoride](image)

![Figure 13. Anti-reflection-coating-life testing.](image)

![Figure 14. Contamination and Cleaning Experiments](image)

![Figure 15. Example wafer: stage purge](image)

![Figure 16. Wafer stage measurement results](image)
Any resist products of exposure are swept away by a curtain of nitrogen. These resist products include strong acids and organics that, under the influence of 157nm radiation, would significantly damage the coatings and final lens elements.

Similar purging precautions are taken at the reticle end of the optical system. Here the major issue is that hydrocarbons and contaminating materials are allowed into the exposure system on the reticles and pellicle systems. Reticle cleaning systems are installed in the system to remove hydrocarbons. Purging systems are designed to remove oxygen and water vapor from pellicle cavities. Porous pellicle frames are used. Figure 17 shows the experimental results of a purge time test on a pellicle frame.

The absorption of 157nm radiation is measured over time while the ambient atmosphere is changed from air to nitrogen. Purge times of a few minutes are typical for the pellicle cavity.

The contamination control system represents a significant part of a 157nm system. All engineered systems are being tested and evaluated on a technology development system so that they are ready to be incorporated in a Twinscan production system (Figure 18).

2.6 Optics

Optical designs have been developed to accommodate the limited availability of optical material choices. Single material designs have focused on the use of calcium fluoride exclusively in combination with mirror elements. The catadioptric designs have been developed to provide enough optical bandwidth to use an un-narrowed fluorine laser. The designs have been progressively developed to deliver higher and higher numerical apertures. Early development systems use 0.75 numerical aperture as standard. Production systems will deliver numerical apertures in excess of 0.80. Design configurations will be narrowed. Figure 19 shows typical design forms that are being worked both at ASML and at Zeiss.

Significant development work at 157nm wavelength will not only produce optics with the highest available numerical aperture, but will also produce illumination systems that will be capable
of supporting the most advanced optical imaging techniques to deliver 50nm lithography. Lithographic solutions are being developed at the ASML Technical Development Center. Imaging is being studied for high numerical apertures combined with alternating phase-shift masks, chrome-less phase-shift masks, and aggressive off-axis illumination such as dipole illumination. Table 1 shows the relationship between NA, wavelength, and K-value (Resolution = Kλ/NA). A K-value of 0.5 represents conventional lithography. A K-value of 0.3 requires strong phase-shift masks or dipole illumination. To reach the 50nm node, numerical apertures in excess of 0.80 will be required with 157nm illumination and phase-shift masks. Figure 20 shows the aerial image of 50nm lines and spaces produced by a 0.95NA system. Figure 21 shows the simulated resist profiles. With suitable resists, 50nm node lithography will be viable. Figure 22 demonstrates the expected depth of focus for the 50nm imaging. Using phase-shift masks, well over 0.5µm is to be expected.

Simulation programs: Mask Tools; (6) Litho-cruiser; Prolith, v. 7.1; and Solid-C are used to explore the lithographic requirements and optimize the 157nm system configuration in association with the 157nm resist systems.

Figure 20. Aerial Image for 50 nm Line/Space using Alternating Phase-shift masks (157nm wavelength, 0.95 NA, sigma 0.2)

Figure 21. Simulated Resist Profiles for 50 nm Line/Space using Alternating Phase-shift masks (157nm wavelength, 0.95 NA, sigma 0.2)

Figure 22. Simulated Depth of focus for 50 nm Line/Space using Alternating Phase-shift masks (157nm wavelength, 0.85 NA, sigma 0.05)

Development systems are now operating at 0.60NA and are being used to develop the required resist systems. These development systems are being upgraded to higher numerical apertures. Figure 23 shows 90nm L/S imagery in 157nm resists. Figure 24 shows 90nm isolated line imagery. Alternating phase-shift masking was used for both resist tests. 157nm resists are still immature, but these early results using exposure tools at Sematech are very encouraging and are paving the way for advances in resist materials. These resist exposures were made in cooperation with IMEC.

Figure 23. 90 nm Line/Space with experimental 157nm resist

Figure 24. 90nm isolated line imagery. Alternating phase-shift masking was used for both resist tests. 157nm resists are still immature, but these early results using exposure tools at Sematech are very encouraging and are paving the way for advances in resist materials. These resist exposures were made in cooperation with IMEC.
3. Summary and conclusion

The 157nm lithography systems continue their rapid development. Significant progress has been made; and continues to be made; in almost all areas. High numerical aperture systems are becoming available. Image quality is improving as new specification optical materials become available at the lithographic system level.

The future is promising for resists with significant progress being made. The prognosis for 157nm lithography is good. It is likely to meet the window of opportunity for the 50nm node.

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References