CVI Laser, LLC
Optical Components & Assemblies

Technical Reference
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Line-Narrowing Etalons

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The 193nm and 248nm DUV-lithography wavelengths place great demands on optics, including line-narrowing etalons, which must withstand high-energy DUV pulses.

The use of Fabry-Perot etalons has significantly improved line-narrowing of lithography sources during the past seven years. Previously, optical filters and prisms were used; however, subpicometer bandwidths and high wavefront quality can only be achieved through the use of an etalon.

Air-spaced Fabry-Perot etalons are the primary means for line-narrowing the output of both 193nm argon fluoride (ArF) and 248nm krypton fluoride (KrF) excimer lasers used in lithography systems. Etalons for lithography applications require high-purity excimer-grade fused-silica plates separated by a flat and parallel optically contacted glass spacer (see Fig. 1). Most etalon spacers are made from a low-thermal-expansion material such as zerodur or ULE (ultra-low-expansion) glass. The inner surfaces of the fused-silica plates are coated with a reflective multilayer dielectric specific for the application wavelength. The outer surfaces are antireflection-coated and wedged to reduce surface losses and prevent extraneous interference patterns from forming.

FIGURE 1. Ring-spaced etalon shown on left. Traditional spacer design shown on right.

An etalon is a filter that functions as a Fabry-Perot interferometer. It consists of two reflective plates separated by an air gap maintained by spacers. Light is reflected back and forth between the reflective plates. When twice the optical distance between the plates equals an integral number of wavelengths, the light passes through the etalon. The sharpness of the transmission peaks and the peak separation are defined as finesse and free spectral range, respectively. (see Fig. 2)

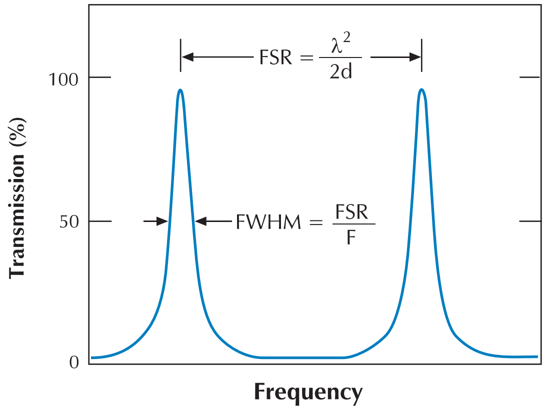

FIGURE 2. Finesse (F) of an etalon is determined by its surface reflectivity, while its free spectral range (FSR) is determined by the spacing between the two reflective elements.

The bandwidth, or full width at half maximum (FWHM), is determined by the free spectral range (FSR) and the effective finesse (F):

$$\mathrm{FWHM} = \frac{\mathrm{FSR}}{F}$$

The thickness of the spacer (or air gap) determines the FSR, expressed in nanometers:

$$\mathrm{FSR} = \frac{\lambda}{2d}$$

where λ is the wavelength and d is the air space.

The principle factors in designing for subpicometer bandwidth are the thickness of the air gap and the effective finesse. The effective finesse is a function of mirror reflectivity, flatness, and parallelism of the coated plates. As reflection of the coated plates approaches 100%, actual finesse is defect-limited by coating absorption and scatter, substrate surface-figure imperfections, and wedge.

Substrate-material selection, surface figure, thin-film coating materials and design, and assembly affect the bandwidth, maximum transmission, and lifetime of the etalon and subsequently the lithography system itself.

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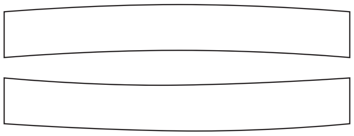
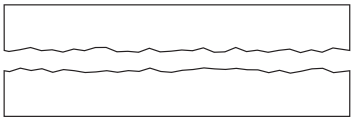
The defects that contribute to this reduced performance:

(graphical representations are exaggerated for clarification)

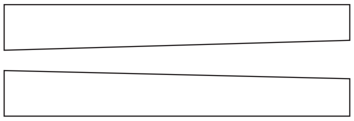
Spherical Defects (Fds)



Surface Irregularities (Fdg)



Parallelism Defects (Fdp)



All three types of defects contribute to the total defect finesse F_d:

$$\frac{1}{F_d^2} = \frac{1}{F_{ds}^2} + \frac{1}{F_{dg}^2} + \frac{1}{F_{dp}^2}$$

The beam divergence also influences the actual finesse of an etalon. Taking into account all these contributions, the effective finesse of an etalon (with F_r being the reflectivity finesse and F_{div} the divergence finesse) is:

$$\frac{1}{F_e} = \sqrt{\left[\frac{1}{F_r^2} + \frac{1}{F_d^2} + \frac{1}{F_{div}^2}\right]}$$

The effective finesse depends not only on the absolute clear aperture, but also on the used aperture of the etalon, especially when a high finesse is required.

Substrate materials

Material selection, final polish, and surface quality affect performance of lithography systems and the lifetime of the optical components within them. Standard UV-grade materials have impurities that lead to low transmittance, high absorption, fluorescence, and/or color-center formation when exposed to high-photon-flux radiation. Damage-mechanism studies of standard UV-grade fused silica under long- and short-term 193nm and 248nm exposure have shown that fused silica exhibits fluorescence due to absorption by impurities. Long-term exposure also leads to eventual internal compaction within the bulk material.[1,2,3] Internal compaction causes unwanted stress-induced birefringence in transmissive optics. Birefringence from compaction degrades the optical performance beyond the precision required in a lithography system. To avoid this, excimer-grade fused silica has been developed to minimize fluorescence and absorption in the 193nm and 248nm wavelength ranges.[4]

For intercavity 193nm and 248nm lenses, windows, output-couplers, and end mirrors, high-purity calcium fluoride (CaF_2) and magnesium fluoride (MgF_2) are the preferred materials because of their compatibility with the fluoride gas used in the laser resonator.

Thermal stability is critically important to maintain a constant air gap in the etalon. Etalon plates for laser line-narrowing are made from excimer-grade fused silica because it has the best thermal performance of the excimer-grade materials. The relatively large thermal-expansion coefficient prevents the use of CaF_2 as etalon plates, as temperature changes impact wavelength accuracy. The thermal-expansion coefficient of CaF_2 is 18.85×10^{-6}/°C, versus $0.57\ 2 \times 10^{-6}$/°C for excimer-grade fused silica; MgF_2 is inbetween: 8.48×10^{-6}/°C or 13.7×10^{-6}/°C, depending on the crystal axis.

Ring-spaced etalons permit cement-free assembly, which is critical for long-life performance. Cement is particularly susceptible to UV degradation. Ring-spaced etalons developed by CVI have been customer tested and survived not only long-term radiation exposure, but have also survived vibrational testing up to 28Gs.

Polishing

Laser-damage thresholds and product lifetimes greatly depend on the final surface polish as determined by surface figure and

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the case of a plano surface corresponds to the deviation from ideal. The spacing between bands is equal to one-half the wavelength of the illumination source. More fringes equates to more deviation from ideal. For best image quality of the laser lithography system, surface figure should be no worse than $\lambda/10$ to $\lambda/20$ at 633nm after coating.

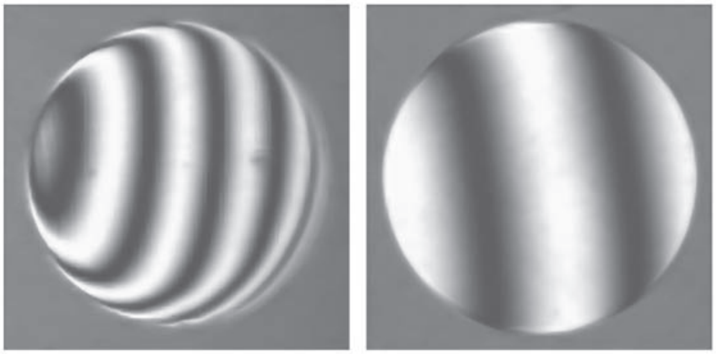

FIGURE 3. As measured interferometrically, flatness of a $\lambda/3$ window (left) is contrasted with that of a $\lambda/20$ window (right).

For etalons, surface figure is not enough to guarantee good performance. The single most important factor in etalon-device performance is the finesse. Since the effective finesse is a function of the flatness of each mirror and the parallelism of the spacer, etalon finesse performance is often the specified parameter. CVI's manufacturing process for etalon plates can achieve $\lambda/100$ after coating, leading to an effective finesse of 30.

Surface quality is defined by the actual number of flaws in an optical surface in terms of scratches and digs. Scratches are defined as the apparent widths of hairline scratches allowed in the surface, specified in units of 0.001mm. Digs are defined as the apparent diameters of defects allowed—such as pinholes, pits, bubbles, and inclusions—in a coating or surface, specified in units of 0.01-mm diameter. Most 193nm and 248nm laser optics must be specified as a 10-5 or better scratch and dig for low-scatter performance; this relates to a scratch of less than or equal to 0.01mm and a dig of less than or equal to 0.05mm. Surface quality is typically measured either by high power microscopes with reticle attachments to magnify and define defect size or an optical comparator to expand the image of the optic under test. Both surface figure and surface quality specified in the preceding manner are considered laser-quality, but also are applicable to critical deep-UV (DUV) light-source-based systems in many semiconductor-processing applications.

Low-absorption, long-life coatings

Final surface cleaning of optics prior to coating is critical to ensure minimal absorption and proper performance of the coating. Good surface cleaning reduces microscopic defects in the substrate surface and coating. Microscopic defects cause increased absorption, localized heating, and ablation, leading to premature coating breakdown by short wavelength laser radiation.

High-purity and low-absorbing coating materials are used to improve efficiency, laser-damage resistance, and durability of all the optics in a lithography system. Specific polarization properties can also be controlled with coating design.

For the 248nm KrF laser line, the most common materials used are silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and hafnium oxide (HfO_2). For the 193nm ArF laser line, typical materials include magnesium fluoride (MgF_2), lanthanum fluoride (LaF_3), yttrium fluoride (YF_3), dysprosium fluoride (DyF_3), thorium fluoride, (ThF_4), and several other fluoride and oxide dielectrics.

For most 193nm coatings, however, the fundamental properties of the available coating materials limit the achievable reflectance and transmittance properties. In a 193nm line-narrowed DUV beam-delivery system, some of the incident radiation can be absorbed or scattered by the beam-turning mirror coatings, so careful selection of appropriate dielectric coating materials is essential. Because there are no high-index nonabsorbing materials suitable for maximum-reflectance coating designs at 193nm, a large number of medium- and low-index coating layers are required to achieve a satisfactory mirror reflectance. Even so, a small percentage of incident laser light can be transmitted through the 193nm mirror coating into the substrate, which makes the choice of a nonabsorbing UV-transmitting substrate such as UV-grade fused silica essential to avoid the potential of laser-induced damage at the substrate surface interface and in the bulk material.

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Improved Etalons from CVI

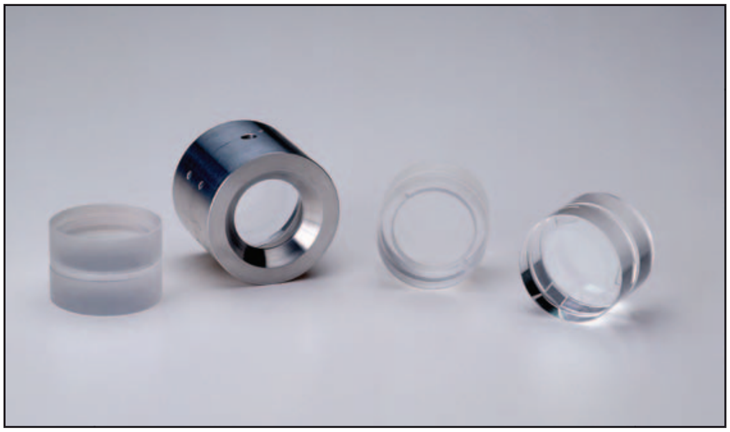

FIGURE 4. CVI manufactures a complete line of etalons: solid etalons, air-spaced etalons and ring-spaced etalons.

CVI has recently improved the performance of antireflection coatings for these wavelengths for damage thresholds up to 2.5 J/cm^2 at repetition rates of 20Hz with 20ns pulse widths. These coatings are well suited for use on transmissive and partially reflective fused-silica beam-steering optics in 193nm and 248nm laser systems. In addition, dielectric UV mirror coatings have survived low-fluence lifetime testing after six months of continuous testing. With proper care, improved coatings such as these make system downtime and frequent replacement-optic maintenance a thing of the past.

CVI's ETR ring spaced etalon leads the industry in mechanical and optical performance. Our etalon manufacturing process regularly attains $\lambda/100$ surface flatness after coating for an effective finesse of 30. Figure 5 shows the difference in transmission characteristics between an etalon with a finesse of 30 versus 10.

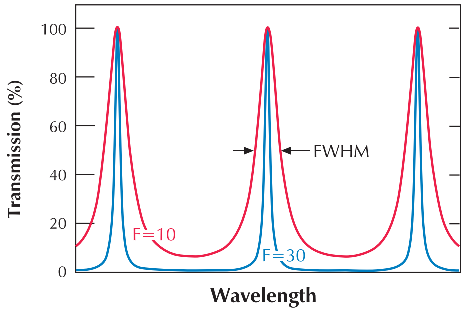

FIGURE 5. An etalon with an effective finesse of 30 versus 10 provides a much narrower FWHM and more complete blocking of out-of-band wavelengths. As shown above, a finesse of 10 allows approximately 10% of the out-of-band wavelengths through which may cause artifacts or compromised performance.

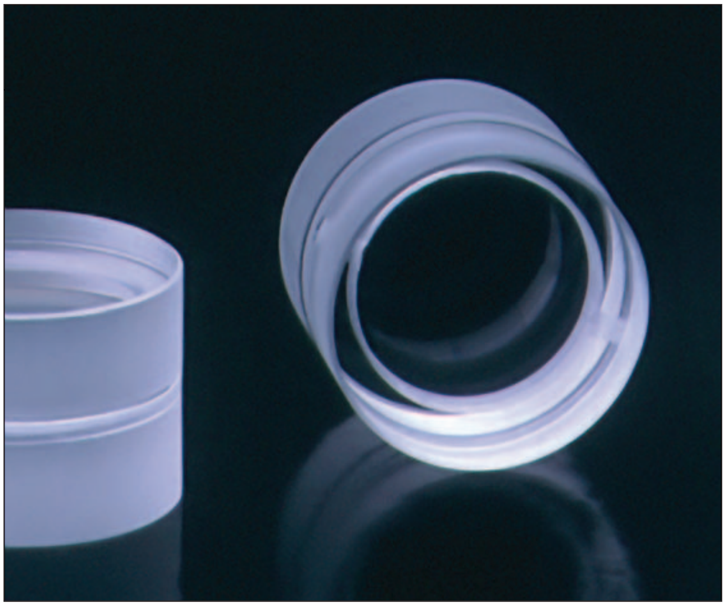

FIGURE 6. Ring-spaced etalons are available in wavelength ranges from 193nm to 1500nm, with air gaps from 25mm to 15mm, and apertures from 15mm to 75mm.

The ring spaced design, see Figure 6, has survived vibrational testing forces up to 28Gs. This extremely rugged design is ideal for cement-free mounting in ultra-violet lithographic exposure systems.

REFERENCES

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