Characteristics of deep UV optics at 193nm & 157nm

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ABSTRACT

The increasing use of Argon Fluoride (ArF) 193nm excimer lasers in microlithography, surgical procedures and other applications have created the requirement for an increasingly larger number of specialized optical components and thin film coatings. At 193nm these include coated components that can withstand long duration exposure to ultraviolet (UV) radiation without significant change in performance. Similar coatings and components for Fluorine (F_2) lasers operating at 157nm are under development. At these deep UV (DUV) wavelengths, potential coating materials as well as substrates are very limited due to absorption and impurities. Characteristics of various types of thin film coatings including reflective, anti-reflective, beam-splitting, beam attenuating and optical bandpass filters, at both 193nm and 157nm, are measured using a specially designed vacuum spectrophotometer system. Results of these measurements as well as plans for further coating development are presented.

Keywords: ArF 193nm and F_2 157nm excimer lasers, Deep UV (DUV), microlithography, optical components, laser damage threshold

1. DUV OPTICAL COMPONENTS

DUV optical components for ArF 193nm and F_2 157nm excimer lasers are primarily designed to reflect, transmit or alter the polarization properties of a specific DUV laser wavelength. These optics are normally manufactured using substrates produced from the highest purity grades of UV transmitting materials including synthetic SiO_2 (Fused Silica), crystalline Calcium Fluoride and Magnesium Fluoride. The proper selection of substrates exhibiting high average DUV transmission free of absorption bands, which are indicated by a drop in DUV transmission, is essential to insure materials are free from impurities that lead to high absorption, fluorescence and/or color center formation when exposed to 193nm or 157nm lasers.

Typical highly efficient DUV optics are coated on one or both surfaces with multi-layer dielectric or metal-dielectric thin films deposited in high vacuum thin film evaporation systems. Thin film coating materials applicable to DUV wavelengths include a limited number of low absorption fluoride and oxide inorganic chemicals such as MgF_2, LaF_3, SiO_2 and Al_2O_3, as well as pure aluminum metal films. Unfortunately, within the dielectric material group applicable for use at 193nm and 157nm there are no high index non-absorbing materials. This lack of a high index material dictates that a larger number of layers of material are required to produce maximum reflectance mirrors in the DUV wavelength region. Also, these coatings typically exhibit rather narrow bandwidths of maximum reflectance. In addition, the high number of coating layers increases the chance of coating defect buildup leading to increased scattering from the deposited films which can lower damage thresholds.

The coatings presented in the accompanying figures were deposited in cryogenically pumped high vacuum evaporation systems via electron beam bombardment and, in some cases, by resistive heating evaporation techniques. Coating layer thicknesses and thin film coating uniformity were precisely controlled with optical and quartz crystal oscillator monitoring techniques. Deposition rates were controlled by the quartz oscillator. Thin film coating designs included both traditional quarter wave coatings as well as non-quarter wave coatings. The non-quarter wave coatings are designed to alter the electric field distribution within the coating layers in an effort to increase damage thresholds, as well as to achieve specific spectral characteristics of the resulting films. Production techniques used in the manufacture of the coatings in the accompanying figures did not include any laser conditioning of the deposited films.

2. REFLECTANCE AND TRANSMITTANCE MEASUREMENT METHOD

For the measurement of DUV optical components below approximately 200nm where light is absorbed by ambient air**,** accurate calibration of the reflectance and transmission properties of 193nm and 157nm coatings is typically determined using vacuum spectrophotometer systems. A vacuum system is used to remove the air from the light path of the spectrophotometer in order to allow transmission of these DUV wavelengths. ARC has developed an automated measurement system,(ARC Model CAMS-507), for the measurement of reflectance and transmission properties of DUV optical components from approximately 120nm to 300nm with high throughput, resulting in strong signal levels and excellent reliability.

The system, as shown in Figure 1, is based on a high resolution 0.75 meter focal length vacuum monochromator, focused deuterium light source with output from 120nm to 300nm, a sample chamber capable of holding multiple samples, DUV detectors and a cryogenic vacuum pumping system. The system operates as a vacuum spectrophotometer in which the source output is scanned and stored on computer. Next, a second scan is made with the optical component in the light path. A third channel continuously monitors source stability for increased measurement accuracy. The two scans are ratioed to yield the optics reflectance, transmittance or absorption properties. Accurate measurement of these properties can be made over a wide angle range from near normal incidence to approximately 74 degrees. Polarizers at 193nm and 157nm have recently been developed and added to the system to facilitate the study of the polarization characteristics of various DUV thin films.

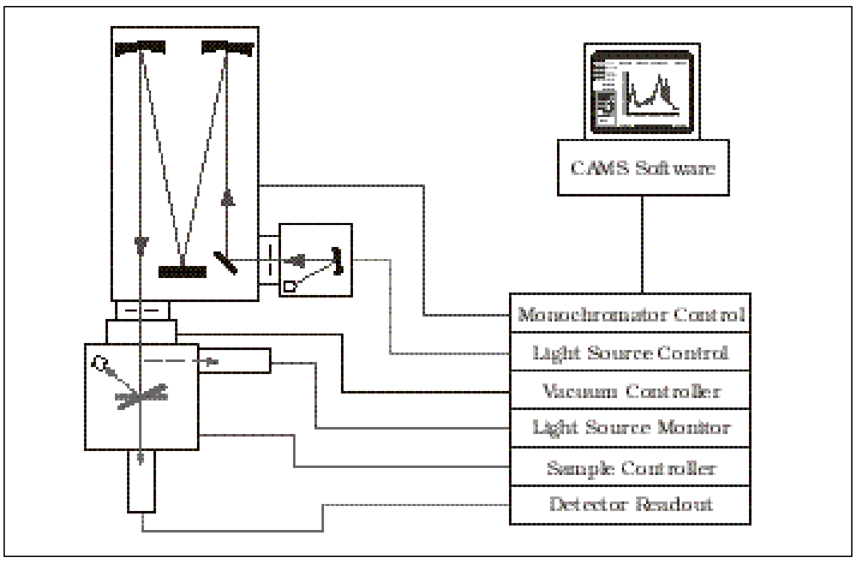

Figure 1: ARC CAMS-507 - Automated Measurement System for Reflectance and Transmission of DUV Optics.

3. DUV MIRRORS

Maximum reflectance DUV mirrors are designed to provide near total reflectance over a narrow or broad range of wavelengths. Typical DUV excimer laser mirrors for 193nm and 157nm are multi-layer dielectric coated optics which are designed to reflect the primary laser wavelength at a specific angle of incidence. The key challenge for UV coating performance is the high photon energy and fluence levels of excimer laser beams used in optical delivery systems[1]. Most maximum reflector DUV excimer laser mirror coatings consist of up to 20 or more “pairs” of deposited alternating dielectric materials which yield narrow bands of reflectance with transmission at wavelengths longer than the design wavelength. Typical normal incidence reflectance (%R) properties of DUV maximum reflectance mirrors is 97-99% R at 193nm and 90-95% R at 157nm as shown in Figures 2 and 3. Beam turning maximum reflectance mirrors designed for a 45 degree angle of incidence yield narrower reflectance bands with %R values 2-3 % less than normal incidence designs; see Figures 4 and 5.

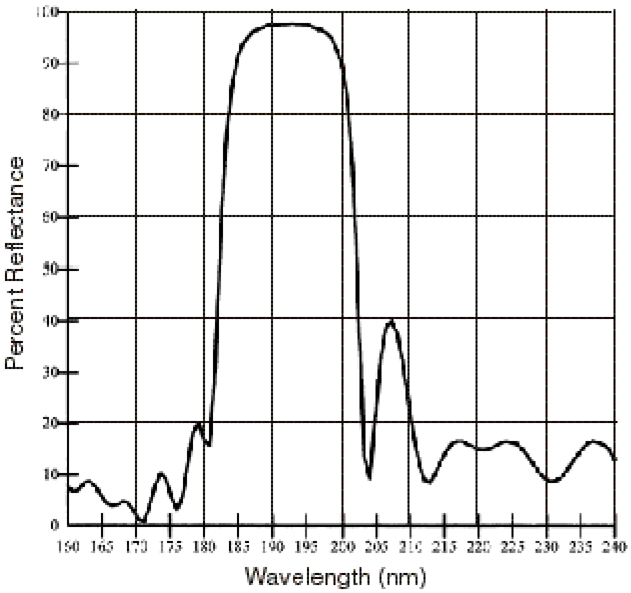

Figure 2: 193nm Multi-Layer Maximum Reflector for Normal Incidence

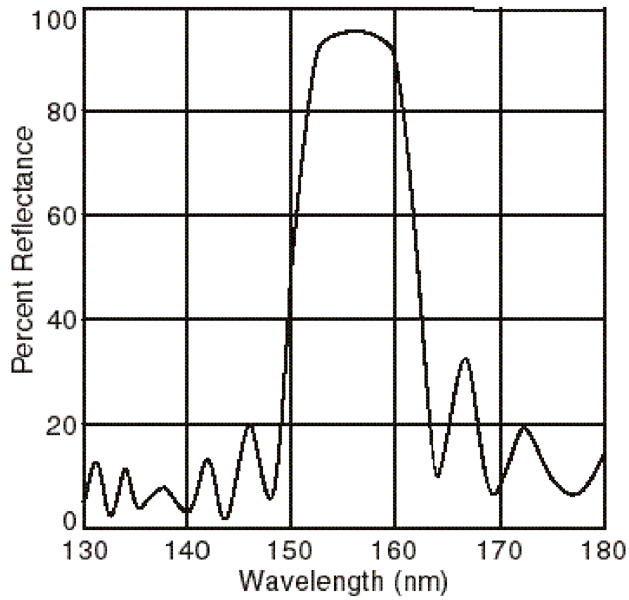

Figure 3: 157nm Multi-Layer Maximum Reflector for Normal Incidence

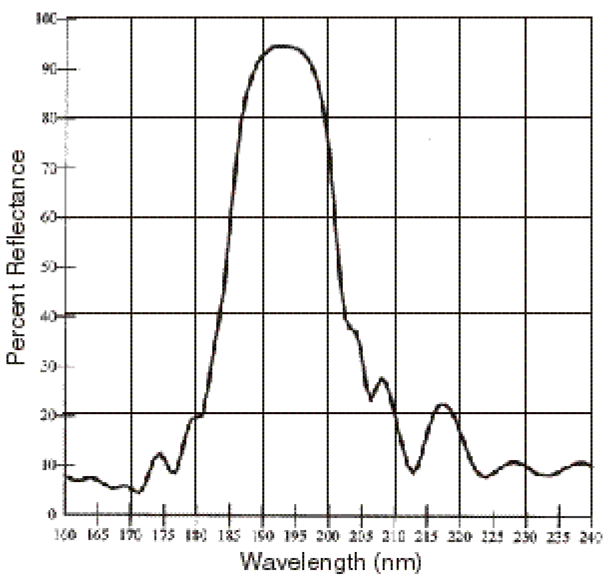

Figure 4: 193nm Multi-Layer Maximum Reflector for 45˚ Angle of Incidence

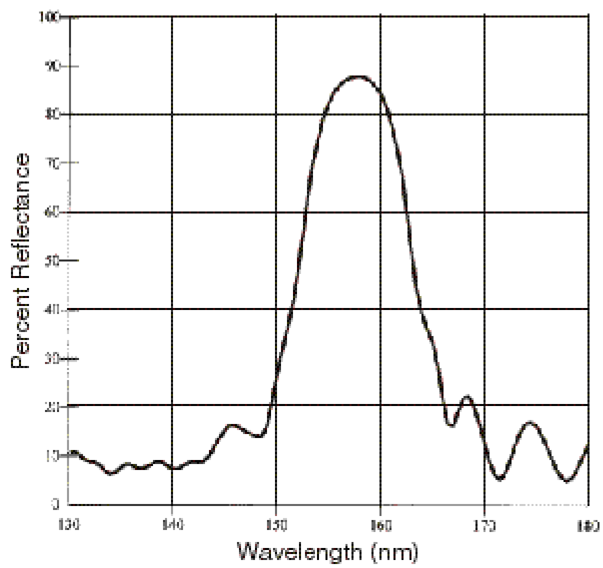

Figure 5: 157nm Multi-Layer Maximum Reflector for 45˚ Angle of Incidence

To date ARC multi-layer dielectric mirror coatings on fused silica substrates designed for maximum reflectance at 193nm at 45 degrees, have a calculated high damage threshold of 1.29 Joules/cm^2. After irradiation at 1.14 Joules/cm^2, 18ns pulse width, for ten thousand shots, no damage in 10 sites was detectable. Long duration, low fluence testing for use in semiconductor applications has yielded lifetimes in excess of 7 billion pulses at 30-40 mj/cm^2 at 400 Hz with no significant degradation in performance[2]. Damage threshold testing of 157nm DUV multi-layer dielectric mirrors is currently planned for the near future. Preliminary low fluence lifetime data has been reported at 5 mj/cm^2 for over ~ 200 million pulses with no damage[3].

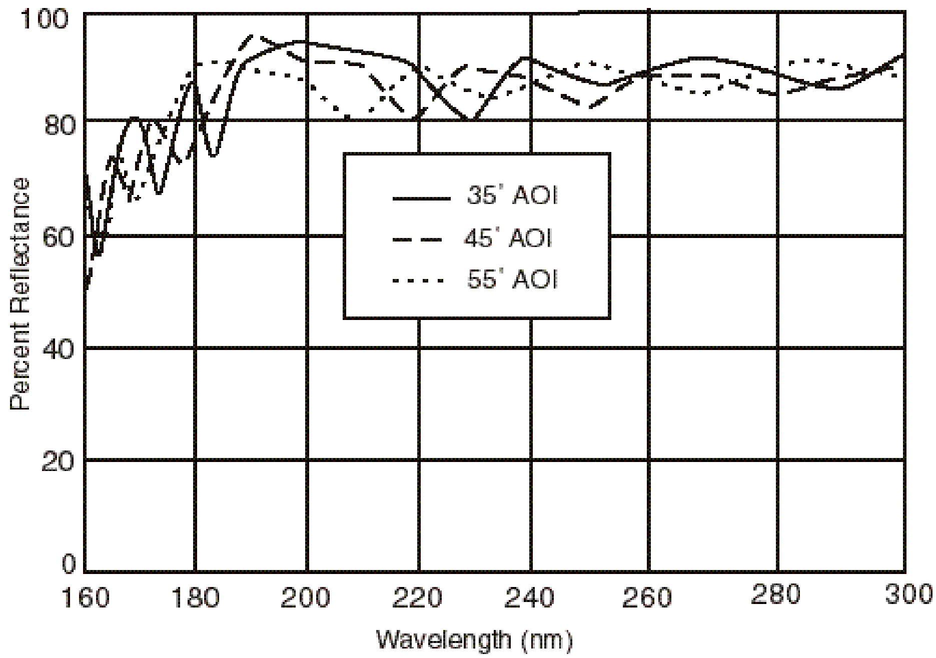

Figure 6: Broad Band Maximum Reflectance Multi-Layer Dielectric Mirrors for 193nm

Broad band maximum reflectance multi-layer dielectric mirrors for 193nm, per Figure 6, have also been produced for applications requiring mirrors to work over a wide range of incident angles. In some applications these broader band multi-layer dielectric mirrors also contain a base layer coating of pure aluminum, which not only enhances the primary UV laser wavelength reflectance, but also provides broad band Visible to IR wavelength reflectance properties. More traditional broad band metallic mirrors containing a base layer of high purity aluminum with a single layer overcoat of magnesium fluoride can be optimized for DUV wavelengths. Typical reflectivity of DUVAl & MgF_2 mirrors yield 88-90% R at 193nm and 84-86% R at 157nm; see Figures 7 & 8. Typical metallic coated mirrors have limited use in DUV laser applications because of their high absorption properties due to the aluminum film, and also yield lower average reflectivity than multi-layer dielectric coatings.

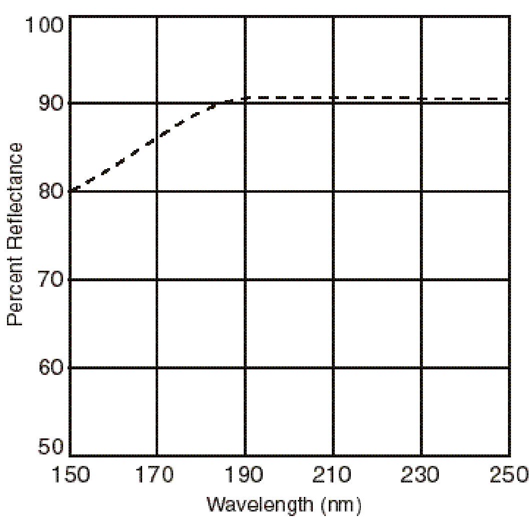

Figure 7: 193nm Al&MgF2 Coating for Normal Incidence

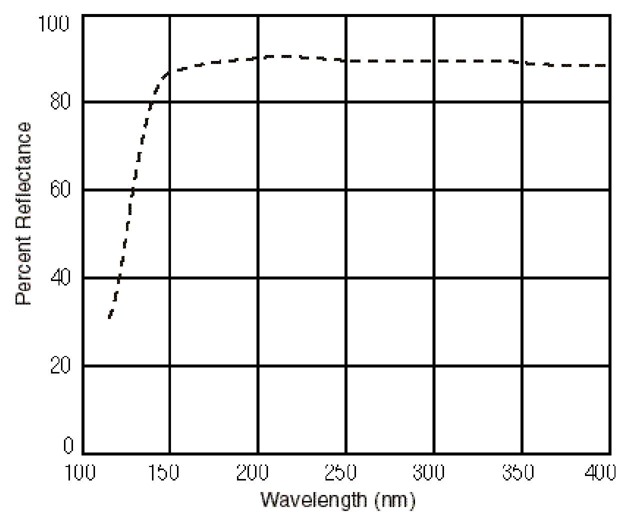

Figure 8: 157nm Al&MgF2 Coating for Normal Incidence

4. DUV ANTI-REFLECTION COATINGS

Anti-Reflection (AR) coated DUV optics include transmitting components such as windows, lenses, beamsplitters and prisms. Typically coated on one or both sides of an optic, an AR coating greatly reduces per surface reflection losses, and hence increases DUV transmission. Many DUV AR coatings at 193nm and 157nm consist of complex multi-layer designs rather than traditional low index one quarter wave designs. These designs produce narrow "V" coatings having low reflectance properties over a limited DUV wavelength region, depending on the refractive index of the optical material being coated and the coating materials used. AR coatings designed for both 157nm and 193nm (on Fused Silica, CaF_2 or MgF_2 optics) typically reduce the reflectance from 4-5% per surface uncoated to less than 0.2-0.5% per surface coated. ARC 193nm AR coatings, (per Figure 9), designed for normal incidence use on CaF_2 optics, have to date withstood 1 billion pulses at 15 mj/cm^2 at 400 Hz continuously without any significant change in optical performance and only a slight discoloration of the coating[4]. At 193nm, certain grades of fused silica substrates can significantly decrease the optics life-time to less than 400 million pulses due to fused silica substrate degradation[5].

At 157nm, similar specially designed AR coatings on CaF_2 substrates (per Figure 10) have to date been exposed to 50 million pulses at an average of 3 mj/cm^2 with more long term testing planned for the near future[6]. More complex multi-layer AR coatings specifically designed for 193nm, at a 73 degree angle of incidence on CaF_2 prisms for 'P'polarized laser light, have been deposited that yield less than 3% reflectance per surface (as shown in Figure 11). Reflectance of CaF_2 prior to coating is approximately 8% per surface at a 73 degree angle of incidence. Careful selection of the materials, both substrate and coating, as well as precise surface polishing and deposition techniques, are all extremely important parameters in the design of this type of DUV laser optic; as high incident angle AR coating performance is degraded by the effects of scattering and absorption.

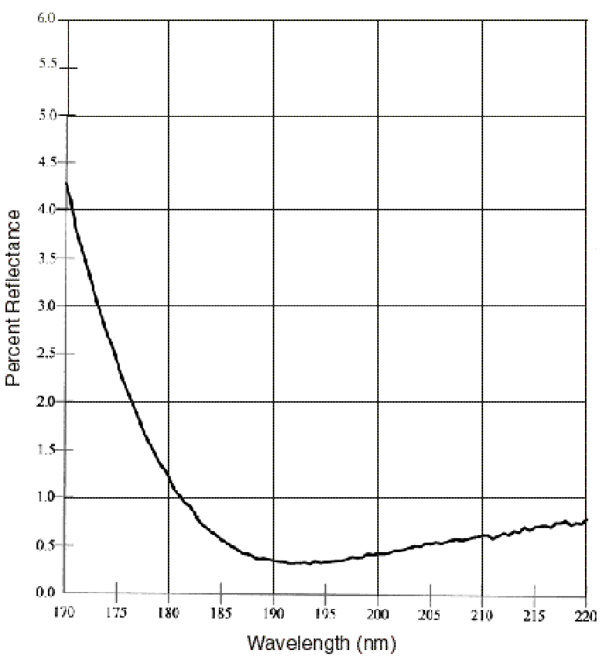

Figure 9: 193nm Multi-Layer Anti-Reflection Coating for Normal Incidence on CaF_2

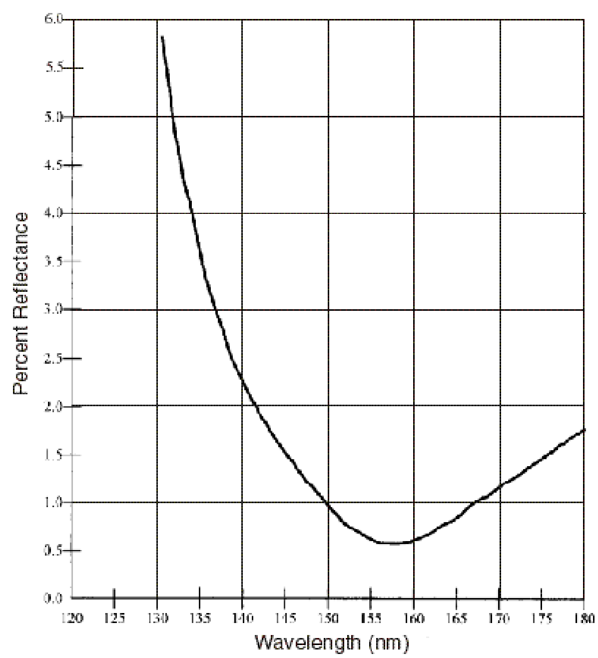

Figure 10: 157nm Multi-Layer Anti-Reflection Coating for Normal Incidence on CaF_2

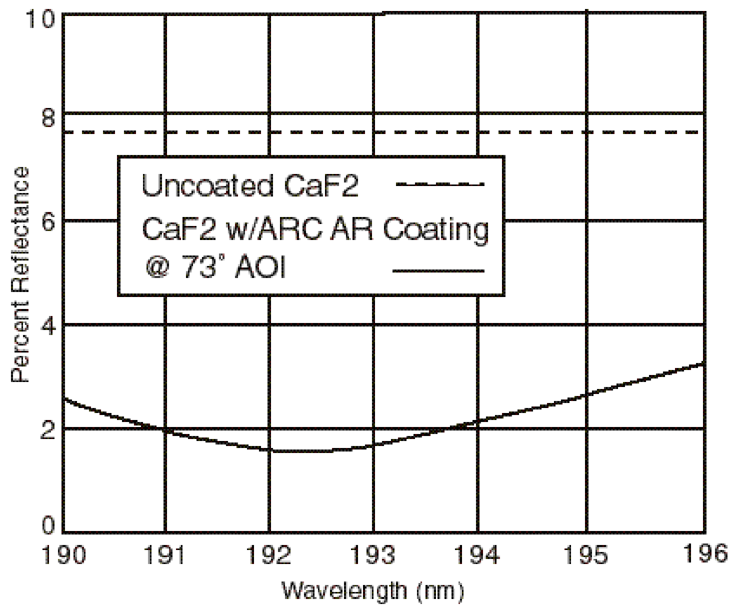

Figure 11: 193nm High Angle Anti-Reflection Coating for 73˚,
P-Polarization on CaF_2

5. DUV BEAMSPLITTERS

DUV beamsplitter optics are specially designed multi-layer dielectric coatings typically deposited on fused silica or CaF_2 substrates. By depositing various medium and low refractive index coating materials of different layer thicknesses and manipulating the number of layers, a specific amount of reflectance and transmittance of the primary laser wavelength can be achieved. The majority of DUV beamsplitter optics are designed for use at a 45 degree angle of incidence. When designed for normal incidence use, they can also be used as fixed beam attenuators to lower the fluence of the laser by a specific amount.

DUV beamsplitters yield broad bands of reflectance, but meet the desired reflectance and transmittance values over a narrow band at the design laser wavelength, as shown in Figure 12. The actual band of reflectance (%R), and hence the resulting transmittance (%T) values at the laser wavelength, is varied depending on the coating design to yield a variety of R & T split ratios. As a partially transmitting optic, beamsplitters that are used in long duration, low fluence applications also require careful selection of the substrate material and surface quality, as substrate degradation can significantly reduce the overall lifetime of the optical component. For beamsplitters with a high transmission ratio of typically 50% or greater, absorption and compaction in some fused silica substrates may reduce the optics lifetime to a few million pulses. ARC fused silica coated beamsplitters designed for a low transmission ratio of approximately 10-30 % at 193nm at 45 degrees, have typically withstood 4 billion pulses of 10 mj/cm^2 at 400 Hz continuously with no coating damage[7]. Long duration, low fluence testing of 157nm DUV Beamsplitter coatings on Excimer grade CaF_2 is currently planned for the near future.

Special variable attenuator optics at 193nm have been designed which typically are multi-layer dielectric coated flat Fused Silica or CaF_2 optics having variable amounts of reflection and transmission with incident angle changes. This type of optic, as shown in Figure 13, allows variation in the amount of ArF laser energy transmitted, by controlling the angle of incidence on the attenuator. These optics can be used in applications for beam attenuation, beam splitting and beam monitoring.

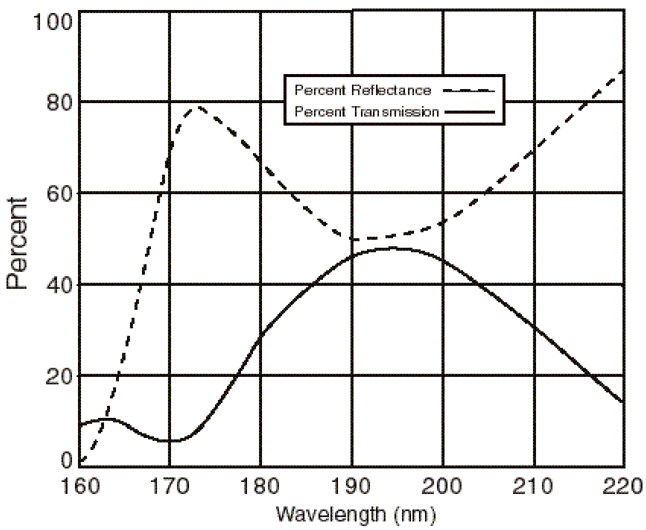

Figure 12: 193nm Multi-Layer 50% Beamsplitter for 45˚ on Fused Silica

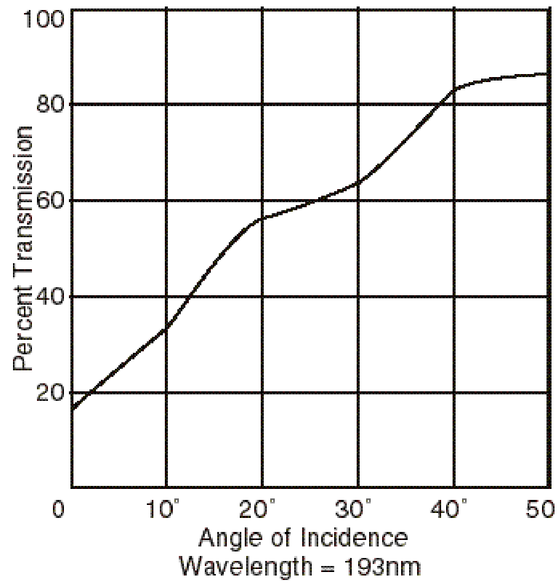

Figure 13: 193nm Multi-Layer Laser Beam Attenuator on Fused Silica

6. DUV OPTICAL BANDPASS FILTERS

Most DUV optical bandpass filters are Fabry-Perot, multi-cavity, Metal-Dielectric-Metal (MDM) coatings deposited onto flat fused silica, quartz or fluoride crystal substrates. MDM filters are designed to transmit a specific spectral band of light, with good rejection of wavelengths outside of the pass band. Typical MDM filters are considered single thin film filters designed to contain one, two or three film cavities with the final top layer consisting of a thin dielectric material. This top layer serves both as an AR coating to optimize filter transmission and as a protective layer against oxidation of the metal film. Typically, filters designed for 193nm are produced on fused silica substrates which provide a transmission cut-off at ~ 165nm. Filters at 157nm filters are produced on a substrate of either cultured quartz (with a cut-off at ~147nm), or CaF_2 (with a cut-off at ~125nm), depending on the filter bandwidth requirements.

Due to the higher absorption of DUV coating materials, most DUV optical filters at 193nm and 157nm have lower peak transmission and wider bandwidths than longer wavelength visible filters. Filters of this type, as shown in Figures 14 & 15, can be designed to have increased peak transmission at the passband, but only with increases in bandwidth. In addition, filters with wider bandwidths have decreased rejection at longer wavelengths. DUV narrow band MDM filters typically have 15-20% peak transmission with a bandwidth of 20-25nm. Broader band designs yield 30-40% peak transmission with a bandwidth of 35-45nm. Long wavelength visible rejection properties of narrow and broad band DUV MDM filters is approximately 10^{-3} to 10^{-4}. Wider band 60-90nm bandwidth filters at both DUV wavelengths can be designed to yield 45-60% peak transmission. However, these filters have limited long wavelength rejection properties of approximately 5% (Visible to near IR transmission) depending on the filter peak wavelength. To date limited laser induced damage testing on 193nm and 157nm optical filters has been performed.

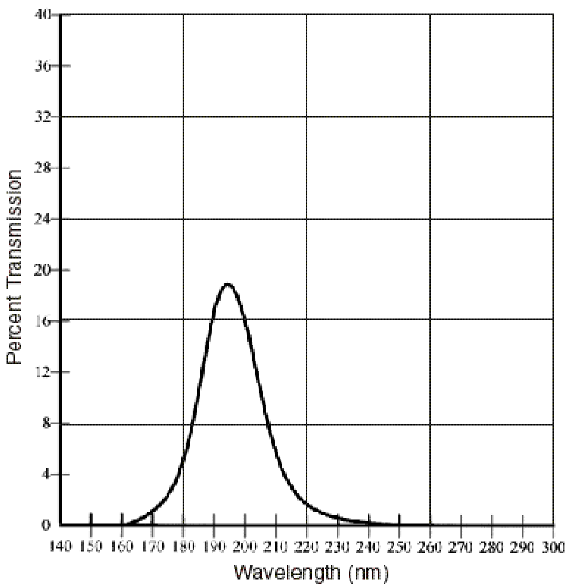

Figure 14: 193nm MDM Narrow Band Filter

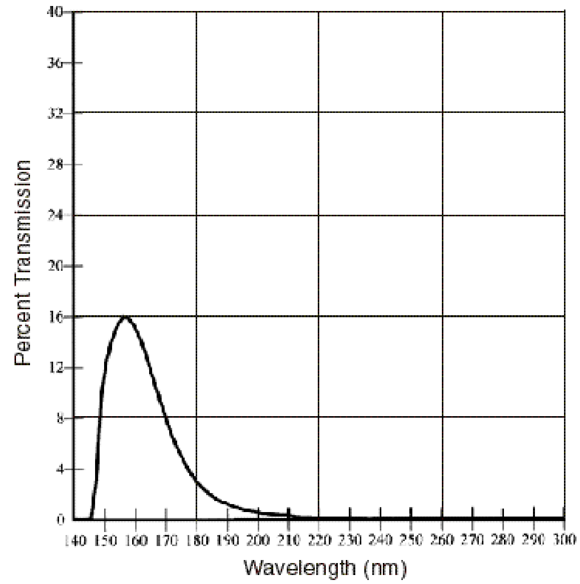

Figure 15: 157nm MDM Narrow Band Filter

7. CONCLUSIONS AND FUTURE RELATED WORK

We have presented the characteristics of various DUV optical components at the ArF 193nm and F_2 157nm laser wavelengths. We have also included an overview of the coating design considerations, spectral characteristics and where available, current laser damage data as it relates to DUV lithography applications. Acton Research Corporation continues to evaluate the laser induced damage thresholds of 193nm and 157nm coatings, as part of an on-going program, with the goal of improving ArF and F_2 optical component lifetimes. Efforts to develop new coating deposition processes, improve substrate quality, research new coating materials and coating designs are currently under way. Results to date in the development of DUV optical components suggests that production worthy DUV Lithography systems utilizing these components can be realized.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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