Growing Demand for UV Optical Filters Drives Advances in Coating Technology

The growth of environmental monitoring, photolithography, materials analysis and processing, and biomedical applications has increased the demand for high-performance optical coatings for the ultraviolet (UV) spectral region. At the same time, modern thin-film deposition processes such as magnetron sputtering enable the manufacture of coatings with improved durability and optical performance.

UV Spectral Region Advantages

The UV spectral region is defined as the wavelength band from approximately 10 – 400 nm. Absorption in air highly attenuates wavelengths below 200 nm, so the near UV (300 – 400 nm) and middle UV (200 – 300 nm) are of the greatest technological and practical interest. The properties of the near and middle UV offer several advantages relative to visible light. One advantage derives from the fact that the photon energies (3 – 6 eV) match the lower electronic excited states of many chemical compounds and materials, leading to optical absorption and photochemical transformations. Another advantage is a direct result of the wave nature of light, in which the limiting resolution of an optical system is proportional to wavelength. Hence, the shorter wavelengths of UV can increase metrology precision and permit the writing and reading of smaller features. These advantages make the UV spectral region important to many applications:

- **Environmental monitoring**. Certain elements and compounds in the environment may be detected by UV absorption and/or fluorescence. A classic example is the detection of mercury by observing the absorption of the 254 nm mercury line using a simple instrument based on a mercury lamp, a bandpass filter centered at 254 nm, and a UV-sensitive detector.
- **Photolithography**. Fabrication of integrated circuits (ICs) having ever-reducing feature sizes drives IC photolithography to ever-shorter wavelengths. Excimer lasers having wavelengths at 157 nm (F_2), 193 nm (ArF), and 248 nm (KrF) are commonly used.
- **Materials analysis and processing.** Materials analysis using UV excited fluorescence and Raman scattering is growing. Sometimes the UV spectral region offers advantages in material processing because of the associated high photon energy. An example is the curing of certain polymers, which crosslink in response to exposure to UV photons.
- **Biological and biomedical**. The high photon energy of UV light enables sterilization of undesirable microorganisms. UV-excited fluorescence techniques are common in biological analysis, and UV radiation is useful for therapeutic and cosmetic medical treatments.

Filter Deposition Technologies

Technology for the creation, manipulation, and detection of UV light is advancing to meet the needs of these applications. One important constituent of UV technology is spectral filtering, or the ability to separate a portion of the spectrum from a beam. Several technologies are employed for filtering, including gratings and holograms, absorbing glasses, and thin-film interference filters. Thin-film filters are generally the preferred choice because of their low cost of implementation, their flexibility (they can be tailored to meet precise filtering requirements), and their durability.

Thin-film optical filters are normally produced using a physical vapor deposition (PVD) process, such as evaporation or sputtering. Early filters were made by thermal evaporation of metal fluorides (MgF_2,CaF_2, and more recently, LaF_2), while aluminum was employed to build metal-dielectric filters. These metal coatings, which tend to be less durable, are referred to as “soft coatings,” and typically must be protected using encapsulation. UV filters were manufactured in much the same way, since until recently, more durable alternatives were not available.

Over the years, technology improvements like electron-beam deposition sources and ion-bombardment sources have improved film durability and broadened the choice of deposition materials. In particular, the choice of refractory materials, such as SiO_2 and Ta_2O_5, combined with ion-assisted deposition (IAD), led to the emergence of “hard coatings” of exceptional durability. Such coatings became widely available in the 80s, and 90s, when ion-beam sputtering (IBS) and magnetron sputtering emerged as important processes for fabricating hard coatings.

Magnetron sputtering employs a magnetic field to confine plasma above a target. The target is held at a negative voltage, inducing ions from the plasma to bombard it. The bombardment ejects target atoms or molecules which are deposited on the substrates to be coated. The high energy of the material impinging on the substrate results in the formation of dense coatings. The process produces films of similar quality to IBS, but with much higher deposition rates and correspondingly lower costs.

Energetic deposition processes like IAD, IBS, and magnetron sputtering, are all capable of producing dense coatings. However, some materials of interest in UV-filter applications are difficult to deposit using these techniques, and some fluorides that are highly transparent in the UV, such as MgF_2 and LaF_2, are problematic. Most work to date using energetic processes for depositing UV coatings has focused on the deposition of metal oxide materials. SiO_2 is transparent and useful over a wide range in the UV, while Ta_2O_5 may be used for near-UV applications as low as 330 or 340 nm. Al_2O_3, Y_2O_3, HfO_2, and Sc_2O_3 have been investigated as materials for use in the mid UV. As expected, these materials form dense, durable coatings; although more investigation is needed to see how far into the UV these materials can be used.

The application of an internally developed magnetron sputter coater to deposit HfO_2 and SiO_2 multilayer coatings for the UV spectral region is described below, beginning with a description of the process and the coating characteristics. followed by a review of representative filters fabricated using the process for a variety of UV applications.

Ucp-1—A Novel High-precision Deposition Process

JDSU used a magnetron-sputter-based coating system developed at our facility to fabricate the filters presented in this paper. The schematic diagram in Figure 1 shows the major components of our Ucp-1 deposition system. A batch of six 200 mm wafers is situated in a double-planetary rotation system in a geometry optimized to ensure excellent uniformity across the planet. Optionally, 200 mm diameter racks containing smaller substrates may be substituted for the wafers. The deposition source is a relatively large circular magnetron-sputtering cathode to maximize deposition rate while maintaining relatively low power density.

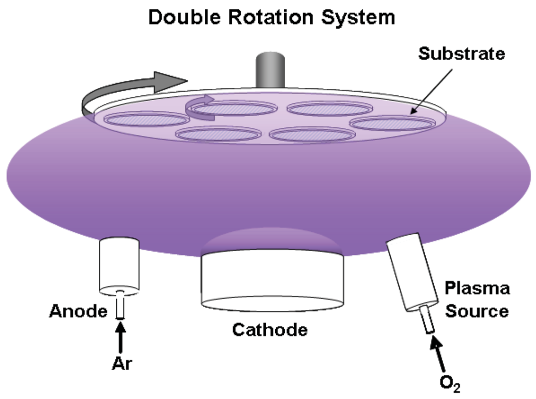

Figure 1: Schematic of Ucp-1 deposition chamber

The sputtering targets may be metals, semiconductors, or sufficiently conductive ceramics. The sputtering working gas, usually argon, is introduced through a small chamber that contains the anode for the sputter discharge electrical circuit. A reactive gas, often oxygen, is introduced through a plasma source. The process has been employed for the deposition of metals, oxides, nitrides, and semiconductors. Most materials are deposited at a high rate; one nanometer per second is typical. SiO_2 is normally used as the low-index material, whereas typical high-index materials are Ta_2O_5 or Nb_2O_5. For the work described here, SiO_2 was the low-index material, and was reactively sputtered using a silicon target. HfO_2 was the high-index material, and was reactively sputtered from a hafnium metal target.

The Ucp-1 system incorporates a load lock that is pumped separately from the deposition chamber, enabling rapid cycle times and therefore greater efficiency. The small batch size of the Ucp-1 system makes it economical for low-volume applications and for prototyping coatings for new applications. The rapid cycle time, and correspondingly high throughput, makes the process cost-competitive for coatings that transition to high-volume production.

Coating Characteristics

The excellent stability of the Ucp-1 process is advantageous for consistently coating thin accurately. This is an especially important attribute for coating UV filters, since the layers tend to be thin. An important measure of the quality of a coating process is its spectral precision, or the accuracy to which a spectral feature may be controlled. Examples of spectral features include the center wavelength of a bandpass filter and the 50 percent transmission cut-off point of a short wave pass filter. The Ucp-1 process has been shown to routinely meet a spectral tolerance of ±0.8 percent and, with appropriate attention to process control, the process may meet a tolerance of better than ±0.4 percent. From a practical perspective, this means that the center wavelength of a UV bandpass filter centered at 250 nm may be controlled to better than ±1 nm.

A transmission electron microscope (TEM) cross-sectional view of an HfO_2/SiO_2 multilayer stack coated with the Ucp-1 process is shown in Figure 2. The structure of the coating fully dense, with no voids or inclusions. This is important, since voids in a coating may take up water and cause a coating's spectral characteristic to vary depending on environmental conditions. Electron diffraction images revealed that the SiO_2 layers in this coating have an amorphous structure, while the HfO_2 layers are polycrystalline. The size of the crystallites in the HfO_2 layers depends on the specific coating processing conditions.

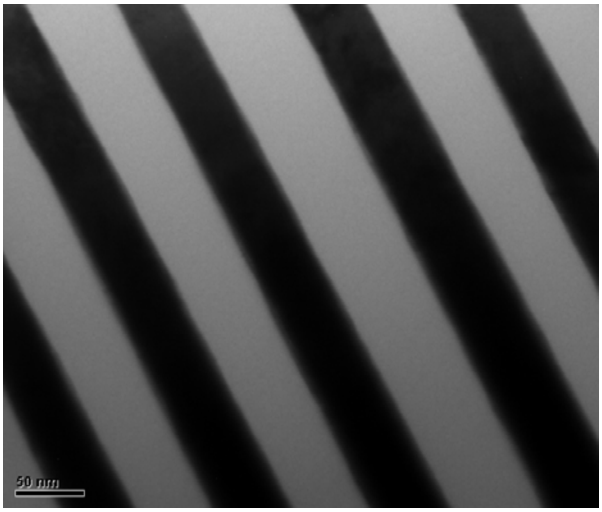

Figure 2: Cross-section TEM picture of HfO2/SiO2 multilayer stack. The dark material is HfO2, while the light material is SiO2.

Metal oxide coatings fabricated with the Ucp-1 process have previously been shown to be very durable [1]. In the current study, UV coatings made from HfO_2 and SiO_2 layers were tested to various durability requirements, including the abrasion, adhesion, and damp heat requirements identified in accepted standards such as MIL-PRF 13830B and ISO 9211-4.

UV Filter Examples

JDSU fabricated several different multilayer filters comprised of HfO_2 and SiO_2 using the Ucp-1 process. Our first example is a bandpass filter centered at 282 nm with a bandwidth of 10 nm, as shown in Figure 3. This filter is typically used for excitation of fluorescence in biomedical applications, such as in-vivo gene imaging or drug monitoring. Strong attenuation between 295 and 950 nm was required for this particular example; the measured average transmittance of the filter is less than 0.03 percent. Despite the many coating layers required to achieve this blocking level, the peak transmittance of this filter is greater than 80 percent.

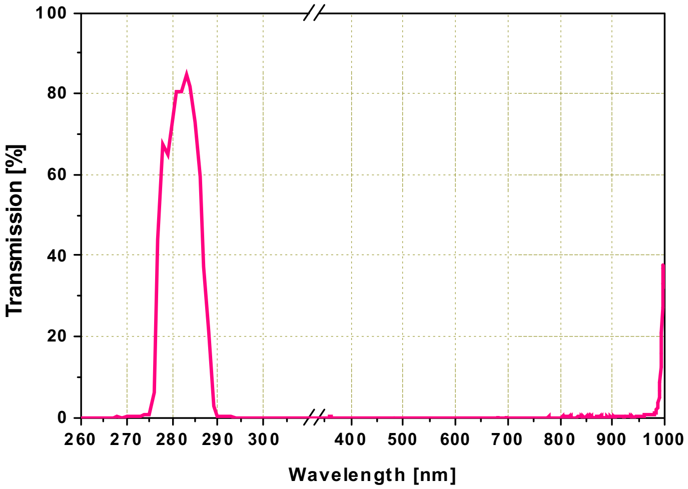

Figure 3: Transmission measurement of 282 nm bandpass filter; the wavelength region below 310 nm is shown on a different linear scale than the blocking region above 350 nm.

Bandpass filters with a center wavelength of 254 nm are used for mercury detection in water monitoring and in crude oil production. UV disinfection devices use 254 nm filters to monitor the output of mercury lamps. Figure 4 shows two examples of bandpass filters centered at 254 nm, both having bandwidths of 10 nm. The difference between the filters is the blocking wavelength range. One filter provides blocking up to 500 nm and exhibits a maximum transmission of 80 percent, while the other provides blocking up to 900 nm but exhibits transmission of only about 60 percent. This example illustrates the tradeoff between blocking range and peak transmission in UV filters; a wider blocking range tends to reduce the peak transmission.

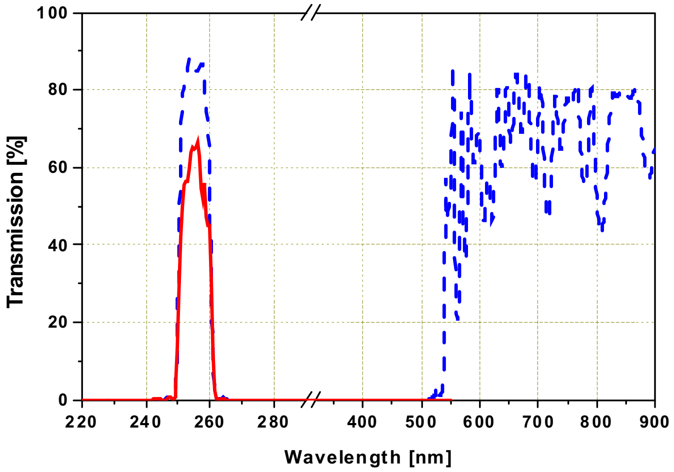

Figure 4: 254 nm bandpass filter with blocking to 500 nm (dashed blue) and blocking to 900 nm (solid red); the wavelength region below 290 nm is shown in a different linear scale as the blocking region above 320 nm.

The semiconductor industry employs 248 nm bandpass filters to clean up the output of krypton fluoride (KrF) lasers used for photolithography. Figure 5 shows the measured performance of a 10 nm-wide bandpass filter centered at 248 nm. This filter incorporates blocking to 550 nm, while achieving a maximum transmission in the filter passband of close to 80 percent.

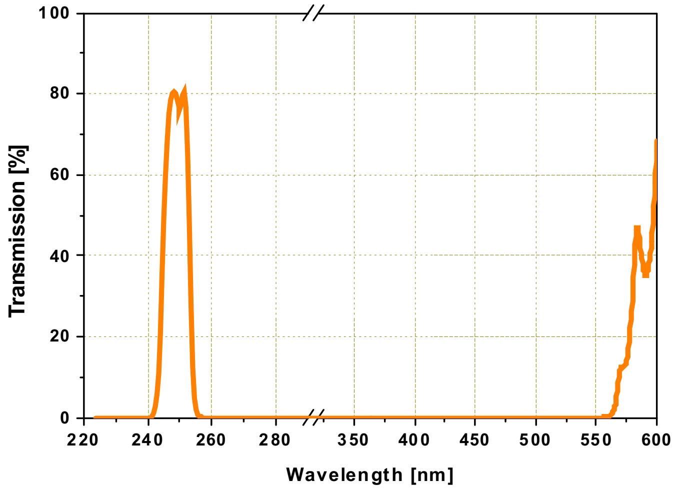

Figure 5: 248 nm bandpass filter with blocking to 550 nm; the wavelength region below 290 nm is shown in a different linear scale as the blocking region above 320 nm.

Figure 6 shows two examples of UV short-wave pass filters that cut off sharply at 400 nm and 500 nm, respectively, and exhibit transmittance of greater than 80 percent down to 250 nm. These filters represent a family of UV pass filters with a spectrally flat high transmission, good long-wave blocking, as well as user-selectable cut-off wavelength, blocking levels, and blocking ranges. These properties enable essentially achromatic UV imaging as required of daylight suppression filters and suppression of light-pollution for astronomical UV imaging. Also, this type of filter is used for broadband UV excitation of visible fluorescence, such as sensing bioaerosols, and broadband UV photochemistry without visible interference.

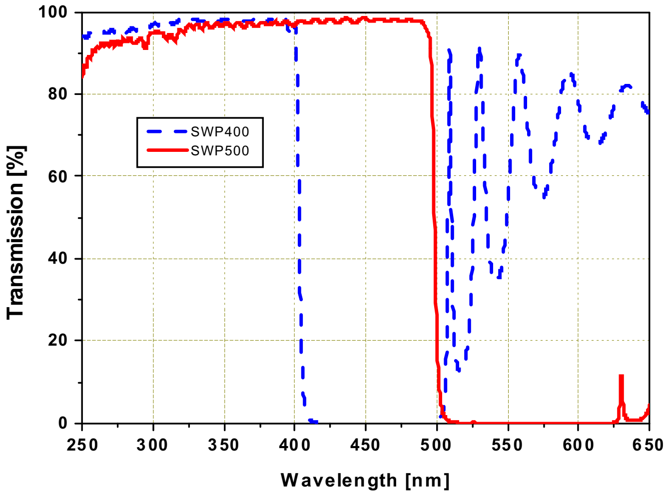

Figure 6: 500 nm (solid red) and 400 nm (dashed blue) short-wave pass filters with blocking to 600 nm and 500 nm, respectively.

Summary

The application of energetic deposition processes to appropriate materials is leading to the availability of durable filters for the UV spectral region. For example, JDSU has shown that coatings comprised of HfO_2 and SiO_2, deposited with the Ucp-1 magnetron sputtering-based deposition process meet the needs of UV-filtering applications requiring transmission at wavelengths as low as 240 nm.

Our conclusion is that, for high-performance optical coatings for the ultraviolet (UV) spectral region the Ucp-1 process is:

- cost-effective and precise
- a high throughput manufacturing process
- maintains a centering accuracy for a bandpass filter of ±1 nm in the UV
- enables high transmission.

A future direction for the development of UV filtering technology is the fabrication of filters for wavelengths below 240 nm. These are more challenging to construct, but a growing demand exists based on the need for improved durability and optical performance.

References

1 R. Sargent, M. Tilsch, G. Ockenfuss, K. Hendrix, M. Grigonis, A. Bergeron, "Advances in Precision Optical Coatings Through the Use of a Fast-Cycle Sputter Coater," Paper O-1, Society of Vacuum Coaters 51st Technical Conference (2008).

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