Creating Complex Coatings

Sputtering advancements ease production of coatings for higher precision and lower cost

The fabrication of high precision optical coatings has historically used evaporative deposition because of high costs and low production volumes associated with sputtering techniques. However, improvements in substrate handling and sputtering production have made sputtering more efficient.
Improved handling techniques, such as load-locked vacuum chambers, have greatly reduced coating chamber downtime. Likewise dual magnetron and advanced plasma reactive sputtering coating platforms have markedly increased filter throughput allowing the fabrication of highly complex coatings with several hundred layers designed to meet the requirements of today's cutting edge applications such as biotech and analytical instrumentation, fluorescence microscopy and advanced spectroscopy.

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For cost reasons evaporative techniques have historically been the preferred methods for creating high precision optical coatings. Recent technology advances, however have resulted in coating equipment based on sputtering techniques capable of producing complex optical coatings of more than 200 layers faster and at lower cost than previous generations. This new equipment deposits coatings with a level of accuracy unmatched by conventional evaporation methods, yielding spectral performance that closely matches theoretical models.

Optical applications in the life sciences, military and laser optic industries are both growing in number and increasing their demands on optical coating fabrication, calling for tighter tolerances in coating designs of increasing complexity. In bio-photonics, for instance, high precision filters are needed for fluorescence applications to maintain separation of excitation and emission wavelengths. These filters must exhibit a fast spectral transition from high transmission in the passband to optical density attenuation levels typically greater than six, for signal/noise (transmission/blocking) ratios of greater than million-to-one. To meet such challenges, the fabrication of optical coatings needs increased precision, greater throughput, and higher yields than traditional methods now produce.

The industry's historically preferred coating fabrication methods uses evaporation. As the name suggests, evaporation is a thermal process in which either resistance heating or electron beam bombardment converts target materials to a vapor that then deposits onto the optical substrate. But evaporation techniques have proven problematic in the fabrication of high precision optical coatings. The energy of the vapor molecules is relatively low – < 1eV – so the film that forms is generally porous and has a columnar microstructure. These films exhibit spectral shift unless energetic ion or plasma assistance helps refine the structure. Also, evaporation deposition rates can vary somewhat with temperature, vacuum pressure, and vapor plume distribution. These variations are not significant with relatively simple products such as antireflection coatings, but can result in lowered yields with complex, multi-layer designs.

An alternative fabrication method uses sputtering, which occurs when energetic ions collide with a target material and, through kinetic energy transfer, cause ejection of target material atoms that then deposit onto the substrate. The energy of these materials is typically 20eV to 30eV, resulting in dense, stable, shift-free films. Because of the highly repeatable sputter actions at the target surface and the relatively

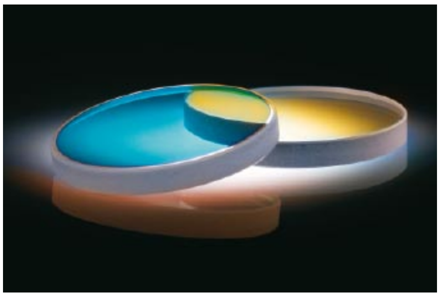

FIGURE 1: **Precision longpass and shortpass filters can be designed for applications where specific wavelengths need to be isolated.**

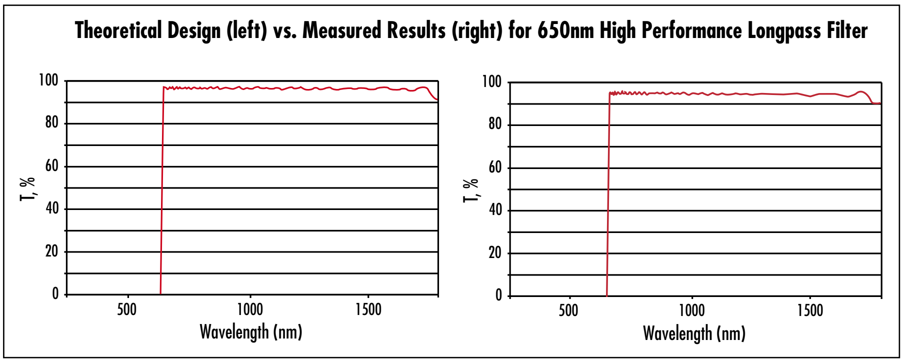

FIGURE 2: **APRS sputtering is able to produce high-performance filters such as this 650 nm longpass that achieve measured performance in near-perfect agreement with theoretical models.**

FIGURE 3: **The Advanced Plasma Reactive Sputtering (APRS) Platform offers the ability to deposit hundreds of highly accurate shift-free layers per single coating run.**

high-energy atoms, the process is also significantly more controllable than evaporation. As a result, sputtering provides consistent, repeatable deposition rates and highly predictable thin film optical characteristics.

Thickness Control Requires Repeatable Rates

This repeatable deposition rate is a critical factor in the creation of a complex multilayer coating, which requires precision control over layer thickness. Usually, single-wavelength optical monitoring techniques that look for turning points in transmission provide such precision and have the additional benefit of being self-correcting. These optical techniques monitor a filter's transmission as the layers grow and cease deposition when transmission reaches its predetermined termination value. By continually evaluating transmission rather than simply monitoring layer thickness, the approach automatically compensates for errors in one layer by adjusting subsequent layers.

For layers that show little change in optical response with increasing thickness, however, a coating system can only control coating thickness using timing. This approach requires the system to accurately know the deposition rate. The system can calibrate for the deposition rate achieved during fabrication under optical monitoring by using measured deposition time and the layer's design thickness, but this is where sputtering techniques are able to significantly outperform evaporation. Deposition rate for sputtering is consistent and predictable over the target life, so the calibration remains consistent throughout the coating process. Evaporation has more systemic variability, such as changes in the evaporation rate and shape of the vapor plume as the target dwindles, that make the calibration less accurate. Evaporation is able to achieve results tolerably close to design theory, but sputtering produces a nearly perfect match (Figure 1 and 2).

In the 1970s the emergence of Ion Beam Sputtering (IBS) technology allowed development of coatings constructed from multiple layers of Tantalum Pentoxide and Silicon Dioxide. These metal oxide coatings exhibited very low absorption and scatter. In the 1990s, IBS was also at the forefront of Dense Wavelength Division Multiplexing (DWDM) filter development efforts that, driven by Telecom requirements, advanced narrowband filter capabilities to new levels.

Despite the advantages that IBS provided, however, only a few companies in North America invested in IBS as their core coating technology. One factor inhibiting investment in IBS technology was the high capital cost – over one million dollars per machine. Also, IBS machines had limited capacity per chamber batch and the hard oxides have a low deposition rate. The result was very long production cycle times and a high cost-per-unit coated part.

Sputtering Advances Speed Production

Over the past decade, then, high-end coating manufacturers have been searching for a technology solution that will provide much of the control and properties of IBS films but with cost per coated part closer to that of evaporation. One such technology, Advanced Plasma Reactive Sputtering (APRS), uses a combination of magnetrons and ion guns to drive material off of a metal target block rather than a metal oxide target for deposition onto a substrate. The method then oxidizes the deposited metals by passing the substrate through an oxygen plasma.

The sputtering of metal targets instead of oxides enables deposition rates close to that of evaporation. The metallic targets are also conductive, which prevents a charge build up that can interfere with sputtering. APRS thus is able to achieve consistent, re-

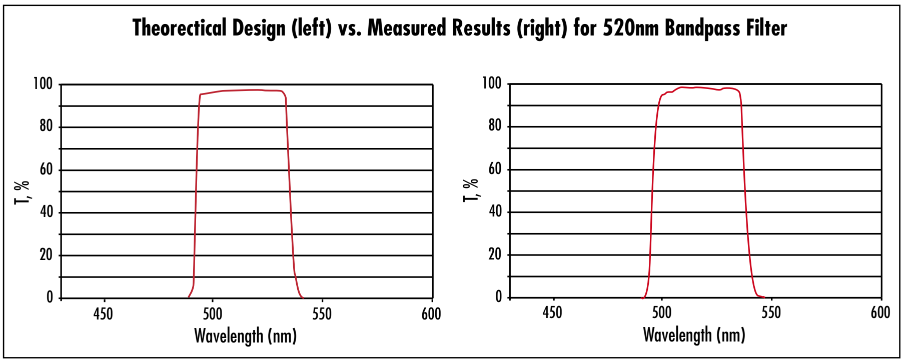

FIGURE 4: **This 113-layer APRS bandpass filter fabricated after only a single test run shows extremely sharp transitions that match theoretical models.**

FIGURE 5: **Chirped Mirrors are designed to eliminate the chromatic dispersion effects of femtosecond pulses in ultrafast lasers.**

peatable rates of deposition with highly predictable thin film optical characteristics and provide a throughput comparable to evaporation systems. One commercial APRS system offers multiple dual-magnetrons, which allows the equipment to alternate the deposition of high-, low- and medium-refractive index materials without needing to change targets (Figure 3). This simplifies the fabrication of complex coating designs such as multi-cavity FP bandpass fluorescence filters that typically have 100- to 200-layer construction to achieve sharp transitions (Figure 4).

Along with the development of APRS technology, sputtering equipment has seen improvement in substrate handling that increases equipment capacity and throughput, lowering unit costs. One such improvement is the use of load locking, which allows the sputtering chamber to remain under vacuum when inserting and removing substrates. Operators load substrates into a secondary chamber that the equipment can evacuate quickly – typically in less than 20 minutes – then open a connecting passage to move the substrates into the sputtering chamber for processing. Eliminating the need to evacuate the main processing chamber with each new substrate run, which can take up to two hours, thus significantly reduces the processing cycle.

A second handling innovation is the use of turntable substrate carriers, which increase system capacity over conventional single-disk substrate holders. Leybold Optics' Helios, for instance, mounts substrates in 100 mm diameter holders, with as many as 16 holders resting on a turntable – a relatively large capacity for high precision coating runs. The turntable rotates at speeds of up to 240 rotations per minute. As the turntable rotates at speeds up to 240 rpm, the system sputters metals from one or both sources onto the substrates. Substrate rotation carries the newly-coated substrates through oxygen plasma to turn the metal coating into an oxide. The high speed of rotation ensures that the oxide layers develop uniformly on all the substrates.

THE COMPANY

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Edmund Optics is a leading producer of optics, imaging, and photonics technology. Supporting the R&D, electronics, semiconductor, biotech and defense markets around the globe; EO products are used in a variety of applications ranging from DNA sequencing to retinal eye scanning to high speed factory automation. EO's state-of-the-art manufacturing capabilities combined with its global distribution network has earned it the position of world's largest supplier of off-the-shelf optical components.

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Precision Enables New Options

The speed and precision with which the new generation of sputtering equipment fabricates coatings has raised the bar on what can be accomplished with multi-layer filter designs. In some military applications, for example, narrow-band reflectors – commonly known as notch filters – are needed to reflect a specific laser wavelength while retaining high-level visible light transmission, so operators can see unimpaired without risking eye damage.

Until recently, however, such notch filters have only been successfully manufactured using rugate technology, where the coating consists of a single layer with a sinusoidally changing refractive index. To obtain spectral performance comparable to a rugate type by using alternating high and low refractive index layers, many of the layers must be extremely thin – often less than 10 nm. Deposition of such thin layers by evaporation methods does not produce homogeneous or repeatable results, and the filters do not show close agreement to theory. Thin layer notch designs manufactured using APRS sputtering, on the other hand, show excellent agreement with theory.

In another example, the emergence of femtosecond pulsed lasers has created a need for "chirped mirrors" (Figure 5) to compensate for pulse broadening and chromatic dispersion effects that arise from multiple reflections in the laser system. These chirped mirrors have a complex layered structure that imparts negative group dispersion to the topical pulse and require very low errors in the deposition of the layers. Production of chirped mirrors by evaporation results in low yields due to relatively high random variations from layer to layer. Initial tests using APRS, on the other hand, show results demonstrating significant performance improvements over evaporation.

Conclusion

The emergence of magnetron sputtering systems such as APRS for the production of high precision coatings is offering not only performance benefits over traditional evaporation but also potential cost savings over traditional sputter technologies such as IBS. As equipment manufacturers develop and introduce larger volume magnetron systems, APRS will likely move beyond exclusive high precision markets, The advantages it provides in producing repeatable high yields along with substrate-handling improvements such as load-lock continuous operation may make these advanced sputtering systems a profitable alternative to evaporation in the medium to low precision markets, as well.