Optical coating technology and applications: past and present to future

Amber Czajkowski, Edmund Optics Inc., Pennsburg, PA, USA

Deposition technology has evolved tremendously since the first single layer optical interference coating was presented more than 70 years ago. Today, methods involving evaporation deposition, IBS, and APRS are amongst the preferred technologies for thin-film production. This article discusses the differences between various coating technologies and their applications.

Increasing demand for high-precision and durable thin films in biophotonic, defense, and laser-driven applications is perpetually propelling the development of cutting-edge technologies and cost-effective manufacturing processes. The article explores the evolution of optical coating technologies and the applications that they are best suited for.

1 Coating fundamentals

The design and development process of thin-film coatings has matured significantly since the first single-layer antireflection coating procedure was invented, realized, and patented in 1935 by Alexander Smakula while working for Carl Zeiss in Jena, Germany. Branded the first practical method of thin-film deposition, he employed vacuum technology to apply a fluoride compound to a glass lens. As a result, adverse reflection effects intrinsic to the glass were eliminated. Not only did Smakula's contribution to optical interference coatings significantly improve the performance of many optical devices, but it prompted a new interest amongst researchers to further explore thin-film technology.

At that time, photographic lenses were the primary application for thin-films; since then, the optical coating industry has grown to serve a versatile market, consisting of approximately $2.1 billion worldwide. Single layer fluoride deposits have morphed into complex multi-layer, multi-functional designs. However, there have consistently remained three requirements for quality optical coating production: (1) a good theoretical design, (2) reliable materials, and, most importantly, (3) a practical deposition process. Fundamental understanding of these key ingredients is what caused the industry to prosper as such.

Each of these ingredients requires profound research and development. Advancements in software and computer technology have rendered a number of very powerful thin-film design programs that can solve sophisticated thin-film equations and develop theoretical solutions to complicated application problems. Additionally, material sciences have significantly contributed to the design and fabrication process. Material selection is quite an arduous process because of the limited number of optical materials suited for coating applications; however, it largely determines a coating's production viability. A theoretical design is virtually useless if it relies upon materials that can't be deposited in an effective way.

Methods including evaporation deposition, ion-beam sputtering (IBS), and advanced plasma reactive sputtering (APRS) are amongst the preferred technologies commonly employed for thin-film production. In the following, each of these processes is analyzed for technological differences, manufacturing efficiency, product performance, costs, and the application or market it best suits.

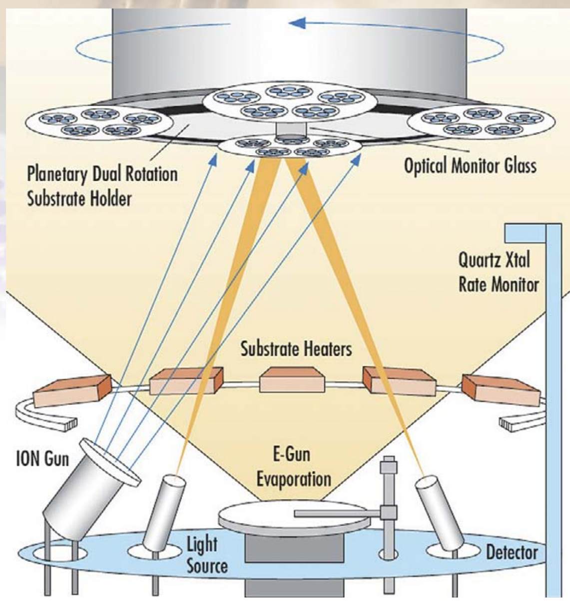

Figure 1: For IAD coating processes at 200–300°C, chamber pressure is typically reduced to <10.7·10^{-6} mbar

2 Evaporation deposition

2.1 Technology

The first effective method used to apply thin-film coatings was evaporation deposition, a thermal process by which source materials are transformed into a vapor state by either resistance heating or electron-beam bombardment inside a vacuum chamber, at pressures on the scale of ~2·10^{-6} to 60·10^{-6} mbar, depending on the type of coating. The evaporated materials then condense and adhere to substrates that are loaded into planetary work-holders, which rotate within the chamber to achieve coating uniformity. The resulting films are generally porous with columnar microstructures exhibiting spectral shift when exposed to varying thermal conditions or changes in humidity; unless the deposition process is enhanced by ion assisted deposition (IAD). In this process variant (**figure 1**), additional bombardment with energetic ions provide for more densely packed layers with less built-in strain and better adhesion to the substrate.

2.2 Capabilities

The evaporation deposition process inflicts fairly low operational costs while being compatible with an assortment of materials, ranging from dielectrics to metals. Additionally, the chamber geometry cre-

Originally published in German in Photonik 1/2010

ates a substantial separation between the material source and the optical parts, leading to superior coating uniformity even with complexly-shaped and steeply curved optical components.
Nevertheless, it is often an unreliable manufacturing process, which is heavily dependent on operator input and, when compared to alternative methods, subject to a greater number of random and systematic errors. This is mostly attributed to changes in process variables such as vapor distribution, rate of deposition, vacuum pressure, temperature, and so forth. Layer-to-layer errors are therefore greater, resulting in inconsistent spectral performance. Furthermore, it takes longer to complete a full coating run in an evaporation chamber, and often at reduced capacity. Depending on the design, it can sometimes take up to two times longer than alternative APRS processes. Since capacity, yield, and production-cycle time are all significant cost drivers, the end-cost of an evaporation produced part is often less than ideal.

2.3 Applications

The evaporation method lends itself well to coating mirrors and most antireflection designs, which have fairly undemanding requirements. It can also be employed on various edge filter, beam splitter, and notch filter designs where the number of layers and design complexity is kept at a minimum; however, once the specifications get too rigorous, accuracy is greatly diminished. For this reason, evaporation deposition is unfavorable for high-precision filters, which can contain > 100 layers. Moderate complexity filters can be fabricated, but this often takes several preliminary tests, resulting in longer development times. For exceedingly demanding filter specs, an alternate fabrication method is necessary.

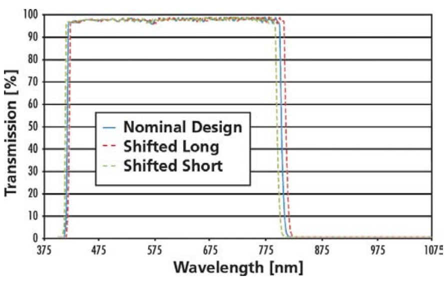

Figure 2: Subsequent to deposition – here: 800 nm high performance shortpass filters – coatings can exhibit adverse spectral shifting when exposed to varying thermal conditions or changes in humidity. More densely packed films greatly reduce this effect

3 Ion-beam sputtering

3.1 Technology

Ion-beam-sputtering (IBS) technology, emergent in the 1970s, allows fabrication of high-precision theoretical designs with impressive accuracy. This sputter process employs an ion gun to produce energetic ions which are accelerated up to tens of eV by an electric field. Once they reach the material target there is transfer of kinetic energy to create a cascade of collisions that ejects, or "sputters," material from the target source. The sputtered particles can ballistically fly from the target to energetically impact the substrate, resulting in deposition. Alternatively, at higher gas pressures (typically inert argon gas), the particles can collide with the gas atoms in the chamber and follow a random path to thermally condense on the substrate, which creates a low-energy deposition alternative. Either way, a hard dense film growth process is accomplished.

3.2 Capabilities

IBS yields the highest quality deposition, resulting in very low-loss, stable, and shift-free optical coatings (**figure 2**). Drawbacks are associated with high equipment costs: A capital investment of more than 500 000 € per machine is required for start-up, and a large amount of maintenance is necessary to keep the ion source operating properly. Other disadvantages include low deposition rates, thus, long production cycles, and relatively small coating run capacities, also resulting in high cost-per-part.

3.3 Applications

Because of its desirable characteristics, IBS technology was at the forefront of narrowband filter development for dense wavelength-division multiplexing (DWDM) in the 1990's. Here, bandpass filters transmit narrow segments of light, while attenuating the surrounding wavelengths. Similar manipulation techniques are used for current-day applications in biomedical, laser, and defense fields, where stringently toleranced bandpass and notch filters are employed to transmit and/or block specific spectral ranges. IBS fulfills these high-precision needs, nevertheless, it's often ruled out as a contender in terms of cost.

4 Advanced plasma reactive sputtering

4.1 Technology

Recent advances in sputtering technology have shown promise of coating equipment which provides much of the control and characteristics of IBS films, but with significantly reduced cost. One example is in advanced plasma reactive sputtering (APRS); more specifically, the commercial APRS system "Helios" by Leybold Optics GmbH, Alzenau, Germany, has nearly revolutionized the coating industry. APRS enables complex coating designs consisting of alternating high and low index target materials. Deposition can exceed 200 layers in a single run, with short production cycles.
The high-precision results demonstrated by APRS-coaters are attributed to recent developments in plasma sputtering, using two dual-magnetron sources (**figure 3**), operating at mid-frequency. Material oxidation is completed when the substrates pass through an oxygen plasma, located along the rotational path of the turntable that carries the substrates. Because the sputtering and the final oxidation process are separated, the targets are not prone to charge build-up effects, which can be problematic in the sputter deposition of metal oxide films. The deposition rate (~0.5nm/sec), which is close to that of evaporation, is well-controlled, resulting in highly predictable films with increased repeatability. Also, since the energy of the APRS deposition method is much higher than evaporation (20–30 eV compared to 1 eV), the outcome is denser, more stable, shift-free films.

4.2 Capabilities

APRS technology produces higher throughput and more environmentally robust coats than evaporation deposition, with faster lead times and improved reproducibility of complex designs. The cost per coated part is similar to evaporation, but significantly reduced in comparison with IBS.

Figure 3: The APRS platform is capable of producing high precision coatings quickly and efficiently, making custom filters more affordable for a wide range of applications

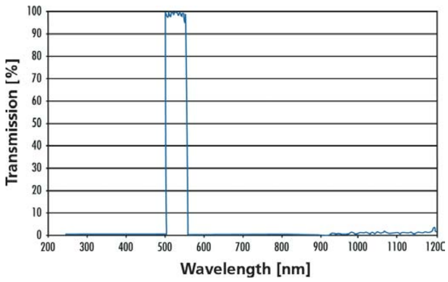

Figure 4: For today's most common fluorophores, tailor-made optical bandpass filters provide OD>6 blocking in the cut-off region and high transmission in the passband, here around 531 nm

APRS is suited for efficiently realizing difficult-to-manufacture coating designs, where high precision, high optical density, high transmission, and steep slopes are key features. These capabilities are critical for capturing emerging markets.

4.3 Applications

Capabilities for this technology extend into the entire range of filter designs including shortpass, longpass, laser-line bandpass, fluorescence bandpass, dichroic, and notch filters. Some of these highly demanded precision filters are discussed below, with reference to some common applications in growth markets of interest.

- Precision bandpass filters can be manufactured for applications in biomedical, laser, and defense fields. In biophotonics, there is an increasing demand for high-precision fluorescence filters with discrete excitation/emission wavelength separation. These filters are typically composed of 100–200 layers in a multi-cavity design for a steep spectral transition from high transmission in the passband to optical-density (OD) attenuation levels >6. This creates signal/noise and transmission/blocking ratios of greater than 10^6:1 (**figure 4**). A specification for a fluorescence filter might be OD>6, transmission >90%, and edge steepness <0.5% over a less than 5 nm to greater than 50 nm FWHM bandpass.
- High-performance edge filters are used in applications ranging anywhere from astronomy to Raman spectroscopy, and designed to isolate specific wavelengths in the long-wave or short-wave regions. Optical densities >6 with transmission >95% in the passband are readily achievable for filters of this sort. The spectral edge tolerance maintains <1% deviation, and can be enhanced to <0.2% for special cases.
- Notch filters are narrowband reflectors used to reflect a specific and potentially destructive laser wavelength, while retaining a high level of out-of-band transmission, e.g. visible light. Coatings of this type are practical for demanding display applications or night-vision systems that need to reject harmful laser radiation. APRS is able to produce thin-layer notch designs with <5% ripple, and OD>6 at the center wavelength, comparable to rugate filter performance.
- Enhanced polarization-controlled multilayers can be manufactured on the first attempt, such that measured performance is almost identical to that of the theoretical design. These typically include beam splitters, whose P- and S-polarization states are manipulated to transmit or reflect depending on the application, or to produce non-polarizing results (**figure 5**). For the latter, the difference between P- and S-polarization can be carefully controlled to well within 5% for a given wavelength and angle of incidence.

5 Technology forecast

In the long-term, it's anticipated that APRS will remain a preferred fabrication method for high-precision filters, with cost potential to extend into lower-end coating markets. Researches continue to explore a High-Power Impulse Magnetron Sputtering technique, known as HIPIMS or HPPMS, due to its excellent adhesion capabilities and extreme durability in aggressive and high temperature environments. This process uses a vacuum technique based on the principle of sputtering, except with much higher power densities (kW/cm^2 range) delivered over very short, 50–200 µs, pulse lengths to heat the target. Another promising technology is that for Directed Vapor Deposition (DVD), which precisely controls the transport of vapor atoms from source to substrate. This process generates higher deposition rates and reduced process times, compared to classic evaporation techniques. However, further development is necessary to apply this technique to optical coating applications of interest.

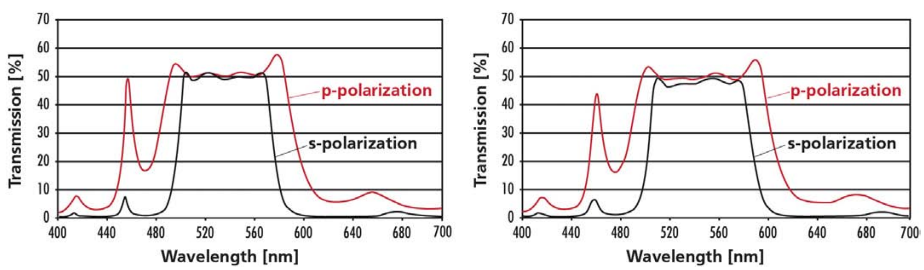

Figure 5: The accuracy of the APRS system becomes evident e.g. in the comparison of the theoretical design (left) vs. measured spectral data (right) for a 532 nm non-polarizing plate beamsplitter

6 Conclusion

As the number of optical applications in the life sciences, military, and laser optic industries continues to grow, the demands on optical coatings extend to designs of increasing complexity with tighter tolerances. Each of the discussed coating technologies presents its own distinct advantages and disadvantages (cf. **table 1**). It was shown that evaporation deposition is well-suited for antireflection and mirror coatings, but when the complexity of the design increases as does cost. One advantage that evaporation deposition holds over APRS is in its ability to coat complex-shaped optics; however, the inaccuracies of evaporation due to random and systematic errors make it unreliable for high-precision tasks. IBS technology is very accurate and favorable to more stringent specs, but the high capital and maintenance costs rule it out for several mainstream applications. From a cost and precision standpoint, APRS deposition technology often outweighs the alternative methods discussed. This is critical in such a competitive industry – where it is essential to maintain high-performance of the optic at a reduced cost.

Literature:

[1] A. Thelen, *Milestones in Optical Coating Technology,* Proc. of SPIE Vol.5963, 2005
[2] P.W. Baumeister, *Optical Coating Technology*, SPIE Press, Bellingham, Washington, 2004
[3] I. MacMillan, *Helios Advanced Capability,* PowerPoint presentation, Apr. 2009
[4] H.A. Macleod, *Optical Thin Films*, from Optical Sciences (OPTI575) class notes, Thin Film Center Inc., Spring 2008
[5] I. MacMillan, *Optical Fabrication: Advances in sputtering benefit coating costs*, Laser Focus World, *www.laserfocusworld.com/articles/358143*, Apr. 2009
[6] R. Jaeger, *Film Deposition, Introduction to Microelectronic Fabrication*, Upper Saddle River, Prentice Hall (2002)
[7] A. Jaunzens, *Versatile coatings all fresh optical properties,* OLE, Feb. 2009
[8] Directed Vapor Technologies, Inc., *Coating Technology for Future,* Charlottesville, VA, *www.directvapor.com*

Originally published in German in Photonik 1/2010

Coating Technologies	Evaporation	IBS	APRS
Capabilities			
Capital Investment & Operational Cost	+ +	-	+
Accomodation (materials, optic shapes)	+ +	(-)	-
Production Capacity	(-)	-	+
Process Reliability & Design Repeatability	(-)	+	+ +
Spectral Precision / Tolerance Capability	- -	+ (+)	+ +
Stability (spectral & adherence)	-	+ +	+ +
Prozess Time	-	- -	+
Applications			
Antireflection Coatings	+ +	+	+
Mirror Coatings	+	+	-
High-Precision Bandpass & Notch Filters	- -	+	+ +
Edge Filters	-	+ (+)	+ +
Polarization Controlled Multilayers	-	+ (+)	+ +
Tight Tolerance Specs and >100 Layer Designs	- -	+ (+)	+ +
+ Favourable, - unfavourable, () neutral / variabel with process parameters			

Table 1: A comparison of coating technologies and applications shows that no single technique provides a solution for all optical coating challenges. For optimum results, a deposition method needs to be chosen based on its capabilities and intended application

Author contact:

Amber Czajkowski
Thin-films Engineer
Edmund Optics Inc.
Manufacturing Department
601 Montgomery Ave.
Pennsburg, PA 18073,
USA
Tel. +1/215/679-6272
Fax +1/856/573-6295
eMail: aczajkowski@edmundoptics.com
Internet: www.edmundoptics.com

Martin Weinacht
Sales Director
Edmund Optics GmbH
Zur Giesserei 19-27
76227 Karlsruhe
Germany
Tel. +49/721/6273730
Fax +49/721/6273750
eMail: mweinacht@edmundoptics.de
Internet: www.edmundoptics.de