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Materials & Deposition Technology for Coating Optical Surfaces

Understanding the Components of the Process

Author: Samuel Pellicori
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The materials and deposition processes employed to make coatings that are intended for use at wavelength regions between UV and far IR are described in this overview of the technology.
Coatings composed of special materials are deposited as nano- and micro- meter thicknesses by specific techniques to control the optical, mechanical, chemical and electrical properties of optical surfaces.

Design & Engineering Considerations for Coating Optical Components

The components of the deposition process, starting with the performance specifications and continuing through the finished coated surface, are diagrammed in Figure 1. It is evident from the number and descriptions of the process components that material science and deposition technology play complex interdependent roles in the overall process of producing optical coatings.

It is important for the system designer to understand the individual components of the process and their interactions. When presented with the spectral and environmental requirements and the substrate material to be coated, the coating engineer has the responsibility of selecting the appropriate coating materials and deposition process. A thin-film design is then generated that includes the wavelength dependencies of the optical constants, refractive index and extinction coefficient - quantities that need to be pre-determined for specific materials and their deposition process parameters. From this theoretical layer-by-layer design, the performance is predicted and evaluated with respect to spectral coverage, incidence angle, surface shape, substrate temperature constraints, mechanical durability and verification measurement.

The technology of preparing the coating material is equally complex and includes consideration of such factors as chemical composition, form, and deposition technique. The starting form of the coating material and its preparation are selected by the engineer based on the deposition technique available and the design prescription. The deposition process' operational parameters, previously determined for each material, are programmed into the deposition controller along with the coating design. These deposition parameters, coupled with material behavior, will determine the physical micro-structural properties of the thin-film layer. In turn, the film properties determine the optical, mechanical and environmental properties of each deposited layer.

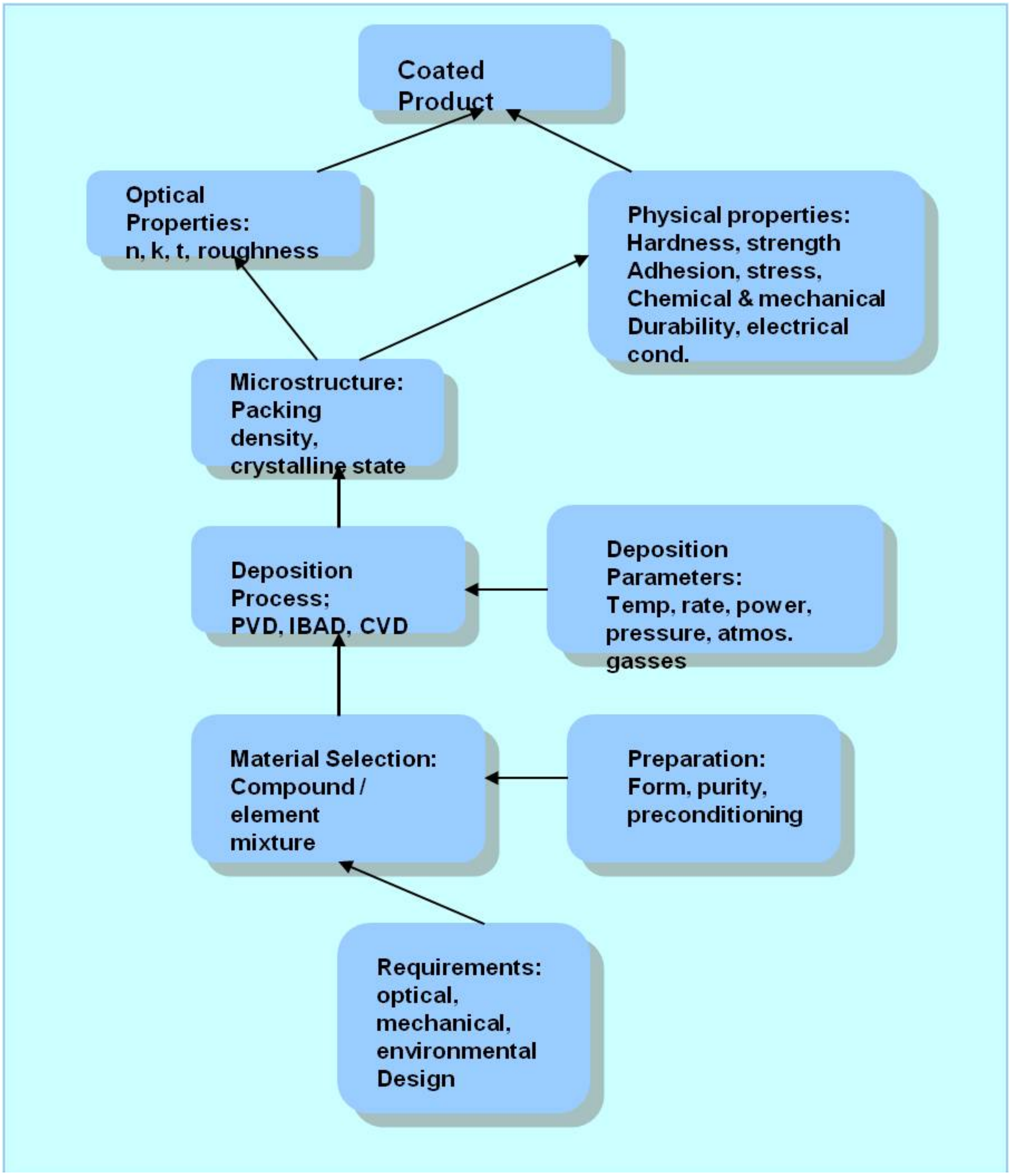

Figure 1. Components of the deposition process of an optical thin film.

The following sections discuss further details related to materials and their applications, and deposition processes.

General Categories of Optical Coating Materials

The intended function of an optical coating determines its layer materials composition and configuration. Design types such as AR, bandpass filter, beam-dividing and combined coatings, high reflectors & laser AR coatings, for example, require dielectric materials whose primary characteristic is the absence of significant absorption. Mirrors that reflect over a wide spectral range are made from highly reflecting metals with protective or enhancing dielectric multi-layers. In *Table 1*, the chemical categories of the materials that are used for optical coating are segregated by spectral region; overlap exists between all regions.

Metal Oxide compounds	Multi-component	Fluoride compounds	II-VI & Semiconductors	Transparent conductors	Metal
Visible - Near IR	UV to IR	UV to IR	SW- to LW IR	Vis-Near-IR	UV-IR

Table 1. Categories of optical coating materials.

Specific Materials Selections

Corresponding to the general materials categories and their wavelength application is a grouping of appropriate materials; for example, those most commonly used for the spectral region of the application. These are listed in *Table 2.* These pure (unmixed) compounds were distilled from dozens of potential materials by how they represent required thin-film layer properties such as: transparency, mechanical properties, environmental durability and ease of deposition.

Table 2 also segregates materials according to their mean high-, intermediate-, and low-refractive indices within the spectral ranges of greatest usefulness, as limited by absorption. Refractive index is a property of key importance in multi-layer coating designs for AR, edge filters, dichroic reflectors, polarizers, laser reflectors, and spectral filters.

Wavelength Region (nm)	**Low index n < 1.6**	**Intermediate n 1.6-1.8**	**High index n ~2**
UV: 250 – 400	MgF_2, SiO_2, CeF_3	Al_2O_3, Y_2O_3	HfO_2, Sc_2O_3
Visible / NIR: 400 -1100	SiO_2, MgF_2	Al_2O_3, Y_2O_3	Ta_2O_5, Nb_2O_5, $LaTiO_3$, TiO_2,
SW-MWIR: 1100 - 5000	SiO_2, CeF_3	Al_2O_3, Y_2O_3, SiO	Ta_2O_5, $LaTiO_3$, HfO_2
LWIR: 5000 – 12000	CeF_3, YF_3, YbF3, ThF_4	--	ZnS, ZnSe, Ge

Table 2. Typical optical coating materials categorized by spectral region and refractive index include pure formulations and not mixtures.

The materials that will be used in the coating design are selected according to the spectral criteria of *Tables 1 and 2*, as well as durability requirements and deposition process. Some materials require preconditioning to prepare them for smooth deposition at a constant rate and consistent composition. The optimal film composition, physical structure, and vaporization behavior throughout the deposition process are strongly dependent on correct preparation of starting material. Coating materials are preprocessed and formed to provide controlled vaporization behavior and to ensure that the physical and optical properties of the deposited film are consistent from run-to-run. Furthermore, the specific compounds listed in *Table 2* require individual forms and preparation.

The chemical material categories are covered in the following sections. Specific materials and applications are also discussed in previous issues of Coating Materials News available on the Materion website [1]. See also the list of coating materials in the Photonics Handbook, available on-line at. http://www.photonics.com/edu/Handbook.aspx

Oxide Compounds for Short-Wave Through-UV Wavelength Applications

Oxide films of the materials listed in Table 2 can be deposited from specially prepared forms by a thermal or E-beam evaporation source or can be sputtered from metal-oxide or pure metal targets. Evaporable metal oxide compounds are supplied in several forms and preparations depending on the particular compound. Typical physical forms are produced as sintered or melted pieces, broken crystals, hot-pressed or cold-pressed tablets, or pre-melted, pre-formed e-beam pocket cones. Cold-pressed and sintered preparations of tablets and pellets of various sizes are made from powder that might be combined with a binder and hot pressed in vacuum or in an inert atmosphere.

Compressed density (>95%) is desired to minimize volume porosity from which water vapor or gas can be released upon heating, a disruptive event. Some oxides adsorb surface water; others form hydrates that dissociate with heat and raise the background pressure (outgas). In addition to causing pressure variation, the release of water vapor or other trapped gas can generate particulates that become incorporated in the coating. In the case of high-energy density environments such as laser applications, embedded particulates set the limiting damage threshold.

The evaporation or sputtering of non-absorbing film layers of oxide compounds requires oxidation to the desired composition. This is done by introducing activated oxygen to the reactive process. The chemical state of the starting material might be fully oxidized or be reduced to a sub-oxide. In the reduced state, material often melts and is conductive, both desirable properties for e-gun vaporization. Materials that evaporate from the melt have a lesser tendency of ejecting microparticulates and spatter (large projectiles) which can result in optical scatter and pinhole creation. When the melt is electrically conducting, e-beam deflection and defocus due to localized charging are eliminated. The reduced forms are gray or black in color vs. white for the fully oxidized insulating material. Re-oxidization is achieved in several ways: by deposition onto a substrate held at temperature >200° C, and by providing an excess of oxygen. Another method is to produce oxygen ions in a reactive plasma process.

The third popular technique is to use an Ion Assist (IAD) source that produces energetic Ar and O ions. If the activation / reactive energies are insufficient to produce a non-absorbing film, post-baking in air at a high temperature (>300° C) might be required.

The low-index oxide common to all oxide coating combinations is SiO_2. Silicon dioxide can be deposited by E-beam evaporation of silica or by reactive oxidation of SiO. Silica does not melt through the bulk of the source, and burrowing of the E-beam must be avoided by employing a sweep pattern for the E-beam. The rotation of the crucible or solid form is used as an alternative to sweeping the beam over granulated silica in E-gun crucibles. Production of SiO_2 films from SiO is not subject to the above problems.

The companion high-index materials for visible thru SW wavelengths are titania, niobia, tantala, hafnia and zirconia. The latter two have transparency extending to ~225 nm in the UV and are the high-index components of UV laser coatings. These materials can be deposited by sputtering the metal. A successful replacement for tantala (Ta_2O_5) is lanthanum titanate ($LaTiO_3$), which is actually a complex chemical compound. Compared to pure tantala, $LaTiO_3$ has several desirable properties when evaporated using E-beam. It requires lower evaporation temperature, which produces denser film layers of lower stress with nearly the same index. Its IR transparency extends to ~8 µm. Titanium dioxide (TiO_2) is a favorite visible-range material due to its high refractive index. It is widely used for applications in AR coatings in the ophthalmic industry and other visible lens coatings.

Numerous deposition techniques involving different oxidation states of the starting preparations have been studied. Analyzing the results, it is noted that to avoid the presence of multiple and unstable crystalline states in the deposited coating and evaporation difficulties, the recommended starting material composition is Ti_3O_5. This sub-oxide composition melts by E-beam and enables smooth, reproducible deposition with the absence of ejected particulates.

Some oxide compounds, and all fluoride compounds, melt before reaching evaporation temperature. Others, including silica, alumina and refractory oxide compounds such as hafnia and zirconia, evaporate from a fused vitreous surface or sublimate (SiO). If the material retains its granular form rather than forming a melt, heat transfer among the grains or pieces is inefficient. This concentrates heat at sharp boundaries like dust, voids, or trapped water sites and can result in the explosive emanation of particles and pressure bursts. Extended preconditioning of materials with a sweeping electron beam can reduce these issues.

Avoiding Problems with Oxide-Layer Deposition

Particulate showering, spatter and pressure bursts are common problems encountered when evaporating oxide compounds. When the starting material is not properly preconditioned or is not an optimal composition, can result in particle emanation ranging in intensity from occasional bursts to continuous showering. Particles in size from nano-meter to multiple-micrometer can be embedded in the layer and cause light scatter or voids (pinholes) when removed by abrasion.

Particulates are the initiation sites for laser damage, and that failure is as important an indicator as absorption in the film in limiting the damage threshold. Particulates become points of mechanical stress concentration and initiation sites for failures such as crazing and cracking. Low packing density micro-structure can permit water penetration. With under-dense starting materials, pressure variation from the release of trapped gases during film layer growth can contribute to inhomogeneity of optical properties, poor stability to variations in humid / arid conditions, and to an upset of the crystal monitor.

Coating technicians reduce these problems through a technique that creates a dense melt by repeated charging of the crucible and melting down to a dense mass. This approach is wasteful of time and resources, so an improved preparation of many oxide compounds has been introduced that increases production efficiency: pre-melted cones that fit the e-beam pocket.

Refractory oxides require evaporation temperatures that range from 1000° C to >2500° C in order to transition from solid to vapor state. Materials with evaporation temperatures >2000° C are: tantala, zirconia, hafnia, alumina, yttria, and scandia. These materials do not melt to a deep pool from which evaporation can precede but instead form a melted/fused spot - essentially a point source. The focused electron beam then burrows a hole whose vapor distribution pattern changes with depth. Rapid sweeping of the e-beam to broaden the source area will reduce thickness- and rate non-uniformities. These problems are essentially non-existent with sputter deposition because of the larger source area and higher pressures involved.

Multi-Component Oxide-Based Materials

The higher evaporation temperature oxide compounds such as zirconia, hafnia and scandia present similar evaporation difficulties as previously noted. They also have optical problems, specifically refractive index inhomogeneity with film thickness. A refractive index gradient in the film layer places uncertainty in the transition from theoretical design to final coating performance. Other oxide compounds, in pure form, suffer inconsistent evaporation behavior such as rate variation. The film itself might contain multiple crystalline states that can transform at high temperature, causing the optical and mechanical properties of the film to be unstable.

Mixed materials, composed of a host oxide and a small percentage of a similar oxide compounds, have been introduced to solve the problems described above. In addition, the mixed materials promote the growth of dense film layer structures because of the incorporation of an additive which discourages the growth of multiple crystalline phases. Instead, a matrix of fine crystallites is assumed to form that is effectively a “pseudo-amorphous” micro-structure. The result is stable properties whether under exposure to high temperature, varying humidity or high energy laser irradiation. Binary and tertiary mixtures have been engineered that exhibit improved stability, reproducibility, hardness and tribological properties along with transparency [1]. Lanthanum titanate is an example of a material that provides improved properties.

High mutual solubility exists among refractory oxide compounds, namely Al_2O_3, In_2O_3, MgO, Y_2O_3, ZrO_2, TiO_2, and Sc_2O_3. This solubility enables admixture with small chemically related materials. The additive proportion is ~10 wt. %. Some examples of available mixtures are: TiO_2-ZrO_2, ZrO_2-MgO, and ZnS-CeF_3. Zirconia is used in UV laser coatings as the high-index layer, however it suffers from high mechanical stress, inhomogeneous index profile and low laser damage tolerance. Mixing it with 25% yttria results in a three-fold increase in damage threshold and improved physical properties. Similar results have been reported with hafnia. Adding MgO to zirconia stabilizes the crystalline state to cubic; adding alumina to zirconia constrains the tetragonal state. In these cases, the nano-structure in not amorphous, but is a stable crystalline state. A ternary composition of these compounds results in an amorphous state. The index of mixtures is a few per cent lower than that for the pure high index component alone. These mixed compositions are available for optical coating applications.

Some demanding coating applications require refractive indices that are not available naturally. Others require smooth rather than discrete interfaces between the high-and low-index layers. By varying the relative proportions of a compatible pair of high- and low- index materials, any intermediate index can be deposited to produce an index value that is not available in a single material. Co-evaporation, co-sputtering, and alternating deposition of two sources are techniques used to accomplish these new indices.

Metal-oxide and -nitride compounds for optical applications can be deposited by admitting the appropriate reactive gas to the sputtering plasma. Similarly, metal carbide and boride compounds used in tribological coatings can be sputter deposited. High deposition rates are achieved by DC magnetron sputtering.

Fluoride Coating Materials

Fluoride compounds and semiconductor layer deposition proceed without the need to supply non-metal components such as oxidizing or nitriding gases; in fact, a high vacuum is required to limit gas incorporation in fluoride film layers. Fluorides retain their chemical composition upon evaporation unless excessively high power is applied, as may occur with E-beam evaporation. For that reason, it is advisable to evaporate fluoride compounds using a minimum E-beam voltage.

Fluoride compounds are evaporated from a melted or sublimated surface. The fluorides that sublime are prepared by vacuum hot pressing followed by sizing. Melting material forms are crushed, pre-melted or crystalline stock that has been refined by remelting and recrystallization. Fluoride bonds are stronger than oxide bonds so dissociation does not occur with thermal evaporation; however, IAD energies are sufficient to break those bonds and permit partial substitution of oxygen and the generation of oxyflouride compositions. Such compositions are highly absorbent in the UV, however, they result in lower laser damage thresholds than achieved with pure oxide or fluoride compounds. For this reason, e-beam and resistance-heated sources are used without IAD for laser applications.

Many fluoride compounds absorb water and must be dehydrated by gentle heating during the melt preparation. Magnesium fluoride as an evaporation material provides the lowest index available for UV to SWIR wavelengths and is prepared by precipitation from solution. Substrate temperatures >250° C are required for the deposition of films with packing density >90%. The nanostructure consists of large columns with high void volume. Residual water absorption bands can be detected in SW region wavelengths (~2.9 µm) to MW (6.2 µm) IR regions - even for depositions made at high temperatures. The quantity of the volatile component of the absorbed water residing within the pores fluctuates dependent on humid and arid conditions, causing the index of the film to vary. Yttrium fluoride, transparent beyond 10 µm wavelength, and other fluoride films also exhibit water bands and index variation when the evaporation conditions are not correct. The water bands in current preparations of ytterbium fluoride (YbF_3) are shallower than those in YF_3 and sometimes absent.

Fluoride films typically exhibit a high tensile stress nature that limit their maximum physical thickness. The coarse growth structure typical of fluoride layers is also responsible for increased light scatter from the rough column ends at the film surface. By admixing small quantities of other fluorides, problems like stress, water absorption, and roughness associated with the coarse nano-structure are reduced or eliminated. LWIR coatings for 8-12 µm have traditionally been built using thorium fluoride, based on its transparency and durability. However, the radioactive nature of ThF_4 has caused it to be eliminated from coatings and multiple studies have been conducted to find a replacement material. Current designs have been using YF_3 and more recently YbF_3. Fluoride mixtures have been employed for many years, some specifically engineered to be non-radioactive replacements for thorium fluoride in IR coating designs. The specific fluoride mixtures that produce dense, amorphous, and stable films are: Materion CIROM-IRX^{TM}, IRB^{TM} and YBaF [1].

II-VI Compounds for LWIR Coatings

Optical coatings that operate to wavelengths ~5 µm can be built from the oxide and fluoride materials previously discussed. Beyond ~5 µm, oxide compounds begin to absorb. Because of that, sulfide and selenide compositions must be substituted along with semiconductors (as shown in *Table 2*) for the medium-to-high-index component. Some fluorides are also usable as the low-index component up to the limit imposed by the thickness-dependent tensile stress level.

The materials used in MW- LWIR coatings, ZnS and ZnSe, sublime and dissociate when evaporated. If substrate surface and chamber atmosphere conditions are favorable during evaporation, the dissociated components will recombine with correct chemical composition at the substrate and produce non-absorbing dense films. While e-beam is a usable evaporation technique, a heated baffled box source is preferred. That is because in the nearly isothermal evaporation environment created, there are fewer hot spots that can produce unrecoverable composition deviations. Typical substrate temperatures used for ZnS and ZnSe deposition are ~150° C.

The high-index component of a LWIR multilayer AR, bandpass, or edge filter is usually germanium with index = 4 which has been evaporated from an e-gun melt. The procedure to obtain non-absorbing films includes eliminating oxygen, and operating at a deposition rate and a substrate temperature that prevent the formation of an oxide. Silicon can be used for SWIR films but it is difficult to avoid the formation of a silicon oxide whose evaporation temperature is much higher than that of the metal. The consequence is production of spatter.

Semiconductor Materials for Solar Power Generation

Thin-film photovoltaic solar cells are being produced using alternative materials to silicon. Their power-generating efficiency is competitive with that achieved by amorphous thin-film silicon. Thin-film layers of direct bandgap semiconductors such as CdTe, CdS and ZnS and multi-compositions, $Cu(In,Ga)Se_2$ (CIGS) and $CuInSe_2$ (CIS) or CuInSSe (CISS) are used to construct the absorber layers in PV cells on glass or flexible substrates. Multi-junction cells can be constructed by varying the bandgaps of the semiconductors to extend their spectral sensitivity. Evaporation of CdS and ZnS layers is a well established technology. Co-evaporation or sputtering is used to deposit the CIGS layer (for example). Layers of PV CdS, ZnTe or CdTe can also be grown from a chemical bath in another construction process.

Transparent Conducting Oxides

Solar cells of all compositions and constructions require a transparent conducting layer as one electrode. The transparent conducting layer is applied over or under the absorber semiconducting layer depending on its character, (ie, its donor function) within the stack that makes up the cell.

Transparent conductors (TCO) are based on adding a few percent of cation or anion donor carrier (responsible for electrical conduction) to a transparent oxide A variety of TCO materials have been developed. ITO, indium-doped tin oxide, has the longest history and widest application. ITO is being replaced by compositions that are less expensive than those containing Indium. Spray pyrolyzed SnO_2 and SnO_2:F are alternates to ITO for solar cell electrodes, as are Cd_2SnO_4 and Zn_2SnO_4. Also receiving current attention are Zinc oxide-based formulations and reacted targets composed of these materials.

Al:doped ZnO (AZO) is among the TCOs being developed as a replacement for ITO, along with IZO (Indium-doped) and GZO (Gallium-doped). AZO is deposited by DC sputtering from a target that contains 2-4% aluminum. Another possible formulation is Al_2O_3: ZnO. Deposition on cold substrates and easier patterning procedures are advantages of AZO over ITO. AZO films are also more transparent than ITO films, but less conductive, and material costs are 1/3 to 1/5 of those for ITO. Lower conductivity is not an issue with transparent electrodes on solar cells.

Deposition Processes

Deposition and growth of thin films for building optical coatings is typically accomplished by one of two physical vapor deposition (PVD) processes: evaporation and sputtering. Chemical Vapor Deposition (CVD) and Atomic Layer Deposition (ALD) use liquid starting materials in their processes. Ion- and plasma- assisted techniques provide additional energy to the evaporation processes to produce compact, dense and therefore stable films with complete oxidation. These techniques are specifically Ion-assisted (IAD) and plasma ion assisted deposition (PIAD). Many ion/plasma sources are available to improve film quality over straight, unassisted PVD processes. Energetic processes are especially important for coatings that will be subjected to harsh environments such as humid, marine, and abrasive / wear (tribological) exposures.

Deposition of films from metal oxide compounds by evaporation or by sputtering can proceed from a preparation of the compound as the starting material. Or they can derive from the base metal and subsequent reactive oxidization to achieve the final desired oxide-compound composition.

Fluoride compounds and low evaporation temperature oxide compounds can be evaporated from resistance-heated sources. The non-oxide materials in *Table 1* generally start and end with similar compositions. To avoid incompatible chemical properties, stress build-up, and process conflicts, the oxide and fluoride chemical classes are generally not combined in a single coating. The exception is with UV coatings where layers are thin and the material selection of transparent materials is small. Multi-component materials have been developed to achieve improvements in one or more thin-film layer properties over the single-element precursor.

Doped fluorides and oxides, and mixtures of two or more chemically similar materials, are typical catalog items from coating materials suppliers. If composition modifications are desired, they can be achieved during co-evaporation or co-sputtering from separate sources of materials. Some benefits from modifying would be chemical and mechanical improvements such as better durability and higher laser damage threshold. For IR coatings that are by nature relatively thick, an advantage would be reduction in tensive stress in fluoride layers as demonstrated by admixture with certain chemically related fluoride materials. Materion CIROM-IRX™ is one example of this.

Controlling Nano-Structural Growth Through Process Parameters

A growth structure problem common to oxide and fluoride films is that of low packing density. Apart from a small number of exceptions (SiO and alumina), thin films tend to grow with a columnar nano-structure unless special measures are adopted. The energy and chemical environments present during growth determine the nature and scale of the structure. For example, when low energy is present at low substrate temperature, the arriving adatoms do not have sufficient mobility energy to nucleate continuous coverage on the surface. Lacking surface mobility, isolated islands nucleate nano-crystallites that then grow in thickness. Subsequent self-shadowing results in the growth of an open structure of columns that have greater diameters at the substrate surface and taper with height. Vapor incidence at large angles can also increase columnar spacing and exaggerate these problems. The porous structure is not only mechanically weak and soft, but is permeable to moisture. Adsorption of water on the walls of the columns increases the effective optical index and also changes intrinsic stress; both properties are unstable to humid and arid exposure. Spectral shifting and stress-induced failure under varying humidity are evidence of under-dense layers.

Film density can be increased to near bulk-like values by increasing the growth energy of the adatoms or by changing the material composition to discourage singular growth dynamics. In preference to resorting to very high substrate temperatures to eliminate optical and mechanical instabilities, IAD is used to apply high energy to the film. In this technique, Ions of oxygen and argon impact the growing film and transfer high kinetic energies, ~100's eV. Greater surface mobility and higher momentum transfer will result in high packing density.

Another method for discouraging low packing density is to introduce an “impurity” which will occupy the spaces and unsatisfied bonds normally accompanying nano-crystallites. This will then interfere with crystalline growth and result in an amorphous, dense structure. The additive should be mutually solvent with the host material and possess other favorable chemical properties. A number of oxide (and fluoride) mixtures have been engineered and are available commercially [1, 2] for this purpose.

Materials that require high vaporization temperatures, such as refractory oxides, often form multiple crystalline phases. This can occur in the e-gun pocket where the temperature difference between areas can exceed several hundred degrees, so that melting and recrystallization occur non-uniformly. The presence in the source of multiple oxidation states and crystal morphologies affects composition and evaporation temperature after repeated evaporations from the same source. The forms possess different refractive indices, stress levels, and evaporation temperatures. Therefore, it would be impossible to achieve repeatable results in subsequent production runs without renewing the composition of the evaporation skin layer. This behavior is characteristic of titanium oxide, zirconia, and other oxide materials. Critical applications such as wide-band AR coatings require that the index of the first thin layer (high index) be repeatable.

Sputtering Materials

Sputter deposition has the advantages of reproducibility and simpler process automation. Multiple variations in the sputter technique have been developed. Optical films can be deposited from a metal target by oxidizing/nitriding sputtered metal ions to deposit an oxide or nitride film layer of the desired composition. DC magnetron sputtering is the technique used for metal targets that are electrically conducting. Oxide (insulating) targets can be sputtered by RF sputtering, but the rate is lower. Practically any material – alloy, mixture, pure metal, ceramic, oxide, nitride, boride, carbide, etc. – can be supplied as a target. Fluorides and sulfides (selenides) are rarely traditionally sputtered because of the hazardous nature of the components and difficulty in maintaining composition.

Summary/Materion Assistance

From the preceding discussion, it is apparent that selecting the appropriate materials and deposition processes for coating optical surfaces poses a challenge. The coating engineer must consider a number of complex factors and requirements to optimize thin film coatings. The engineers at Materion, with their long history of expertise in thin film deposition, can partner with you to identify appropriate materials and best processes for your optical coating needs. For more information, contact Andrew Cohen, Project Marketing Manager, Andrew.Cohen@Materion.com

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Principal Contributor

Samuel Pellicori, Pellicori Optical Consulting, Santa Barbara, CA
Phone: 805.682.1922, Email: pellopt@cox.net

Materion Advanced Materials Group
2978 Main Street
Buffalo, NY 14214
+1 800.327.1355
www.materion.com/advancedmaterials

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