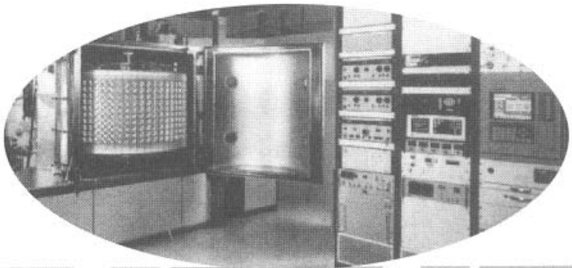

WHITHER OPTICAL COATINGS?

By Philip Baumeister

What are the similarities between the reflected colors of mother of pearl, an oil slick on water, and a multilayer optical coating? All are manifestations of *optical interference.* This article focuses on the interference effects in such a multilayer coating and how it may either increase or decrease the reflectance of the surface that underlies it—the substrate. A few applications of such coatings are mentioned, as well as some new and emerging techniques of producing them.

Snapshot: The article discusses a simple model of optical interference in a thin layer, the evolution of new methods for depositing thin films, and markets served by optical coatings.

So, how does interference function? The simplest example is a single non-absorbing layer. Figure 1 shows the spectral reflectance of such a layer deposited on a glass substrate of refractive index 1.65. Each surface of this substrate would reflect 6% if it were uncoated. The application of a low index layer of magnesium fluoride (n = 1.38) reduces the reflectance to 0.5% (left panel), whereas the application of a film of higher index (n=1.85) increases its reflectance (right panel). The interference effects in the layers explain this phenomena.

Consider the reflected beams in Figure 1. The light and dark bands represent maxima and minima of the amplitude of that wave. A portion of the wave also penetrates the layer and reflects at the film-substrate interface—this is (b). That reflected wave then emerges into air at (d) and is either *in phase* or *out of phase* with wave (c), which is the wave reflected at the outer interface.

For the left panel of Figure 1, the layer is of *higher* refractive index than the substrate. The (c) and (d) waves are *in phase* and a maximum reflectance results. In the upper portion of Figure 1 is a "snapshot" of the amplitudes of these waves. The solid is the incident component. The dashed curves represent the reflections from the two interfaces—these waves are in phase. This is manifested

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as a 12% peak reflectance in the graph. This is called "constructive interference" in books on physical optics.

The right panel depicts a lower refractive index layer. The wave reflected from the air-film interface and the wave reflected from the film-substrate interface are 180° out of phase. Physical optics texts term this "destructive interference." The result is that the reflectance is lowered from 6% (for the uncoated substrate) to nearly zero.

The net reflectance cited above depends on the thicknesses of the layers relative to the wavelength. The optical thicknesses of the layers in Figure 1 are quarter-waves at 530 nm, which is the reason that a maximum (or minimum) reflectance occurs at that wavelength. The reflectance curves could be shifted to a shorter wavelength by reducing the layer thicknesses. A thickening of a layer shifts the reflectance maxima to longer wavelengths.

Genesis of optical coatings

The theory of interference mentioned above was well understood by classical physicists such as Fizeau and Rayleigh. The problem was that there was a paucity of methods of depositing a solid, physically durable layer on a glass surface. The technology evolved in the 1930s. In that era, companies such as Carl Zeiss[1] (Jena, Germany) and Bausch and Lomb[2] (Rochester, New York) deposited anti-reflection coatings by vacuum evaporation. The apparatus of that period is depicted in Figure 2. A glass bell jar was sealed by a rubber gasket to a metal base plate. Previously the lenses to be coated were loaded into a rack in the upper part of the jar. Pumps then evacuated the enclosure to a relatively low pressure. In the bottom of the jar there was a heater that evaporated magnesium fluoride. The molecules of MgF_2 condensed as a solid film on the glass surfaces—a monomolecular layer at a time. The deposition was terminated when the correct thickness for the layer was attained.

More sophisticated deposition equipment evolved in the 1960s and 1970s. A welded stainless steel box replaced the glass bell, a cryopump supplanted the oil diffusion pump, and an electron beam evaporation source was used in lieu of the resistively heated boat. On-line computer control of the coating process has been implemented, although not as widely as one might think.

What coatings can accomplish

Since the 1940s, the apparatus in which coatings are deposited has grown in complexity. A consequence is that sophisticated coatings are now produced that may contain many hundreds of layers. In some instances, entire industries have become dependent on coating technology. A few of the larger markets for coatings follow:

Lasers

Every laser has at least two mirrors that provide the feedback of the amplifying medium. The mirrors are usually multilayer dielectric because of their low absorption. Reflectances in excess of 99.99% are commonly achieved in laser gyros. In contrast, the aluminum layer mentioned above has a reflectance that hovers at 90% in the visible portion of the spectrum.

Visual Display Terminals

The cathode ray tube of a computer monitor is an example of a visual display terminal (VDT). The contrast of the display is degraded by the background illumination—the ambient room light. The contrast is enhanced by covering the display with an absorbing panel. An antireflection coating (AR) is applied to the surfaces of this panel. An area approaching a fraction of a square kilometer of such coated panels are produced yearly.

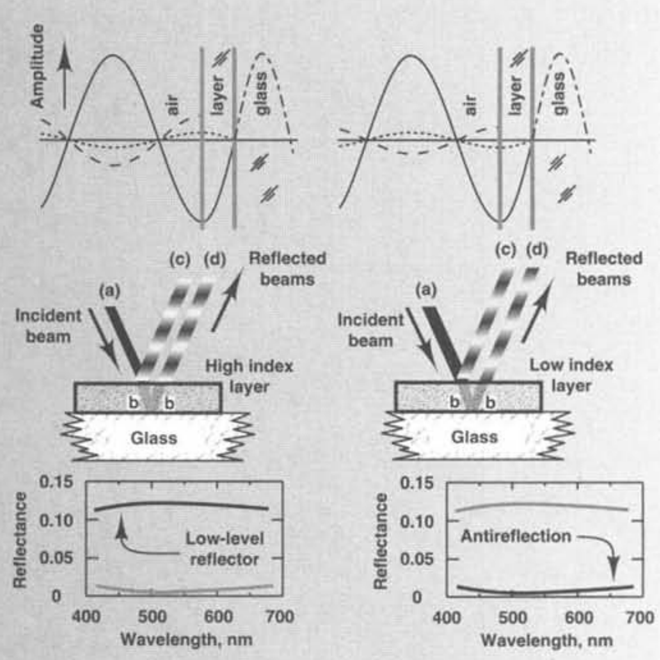

Figure 1: Quarterwave optical thickness films of index 1.85 (*left panels*) and 1.38 (*right panels*) are deposited on a substrate of index 1.65. In upper graphs, amplitude of the incident wave component (*solid*), component reflected at the air-film interface (*long dash*) and reflected component at the film-glass interface (*short dash*).

Ophthalmic

Hundreds of millions of eyeglasses are produced yearly throughout the world. In Europe and Japan it is quite common to add anti-reflection coatings to the lenses.

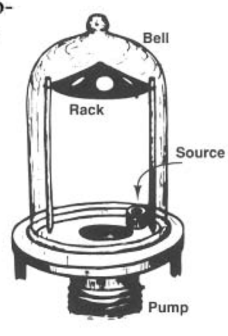

Figure 2: Bell jar for the deposition of films in a vacuum by evaporation from the *source*. The *rack* holds the lenses to be coated.

Analytical instruments

Many analytical instruments determine the concentration of a chemical constituent by measuring the amount of light it absorbs at some particular wavelength. A filter isolates that wavelength. An example is the photometer that measures the uric content of the blood serum. A multilayer bandpass filter isolates its absorption band at 291 nm. Although a diffraction grating or prism could be used, a multilayer is preferred because of its lower cost and compactness.

Color TV cameras[7]

A higher quality color TV camera uses dichroic beam-dividers that split the light into the red, green and blue channels, as shown in Figure 3. Each prism coated a with dielectric multilayer that reflects and transmits the red, green or blue spectral bands.

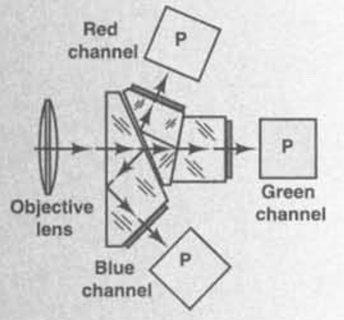

Figure 3: In a color TV camera, dichroic coatings on glass prisms direct the light to the receptor tube P in each of the color channels.

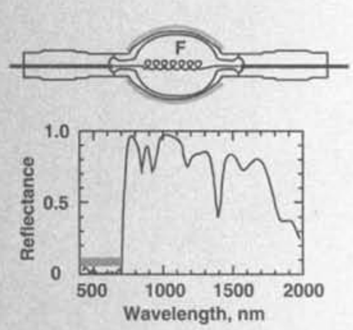

Figure 4: (Upper) A regenerative coating (*shaded*) is applied to the exterior of a quartz-halogen light bulb. (Lower) Reflectance of the coating. From data of Bergman.[8]

Lighting[8]

A rapidly expanding field is the use of a regenerative coating on a quartz-halogen light bulb, as shown in Figure 4. The figure shows that the reflectance of the coating is low in the visible and high in the near infrared. The reflected infrared reheats the filament and visible radiation escapes. The gain of this system is typically 1.35. That is, 35% less electrical input power is consumed to produce the same amount of visible light.

Manufacture of coatings

It is estimated that the optical coating industry has yearly sales of at least $700 million in the U.S. alone. This excludes the architectural coatings mentioned below. It is axiomatic that the method used to produce a coating is influenced strongly by the equipment that may be readily purchased, as well as the availability of engineers and technicians who are trained in its operation. In the Western Hemisphere, Japan and Europe, vacuum evaporation equipment may be purchased from many vendors. It is not surprising that this is the predominant way that optical coatings are presently manufactured. There are, however, other deposition methods that deserve mention: (1) magnetron sputtering; (2) chemical vapor deposition; and (3) pulsed plasma chemical vapor deposition.

Planar magnetron sputtering

Sputtering[3] is a process in which an energetic ion hits a cathode and transfers momentum to the atoms at the cathode's surface. Some of those atoms are physically dislodged by this process. Magnetron sputtering is efficient because the ions are magnetically confined at the surface of the cathode. The machines that coat glass for architectural purposes use magnetrons. There are at least 100 such machines in the world that yearly coat many square kilometers of glass for the exterior of buildings. Sputtering provides a high rate of deposition and superior physical density of films. For this reason, magnetron sputtering may displace vacuum evaporation in many applications.

Chemical vapor deposition

Chemical vapor depesotion, referred to as CVD,[4] has been used in the semiconductor industry for many years. The deposition of a barrier silica layer is an example. In this process, the parts to be coated are loaded into an enclosure surrounded by an oven. After the enclosure has been evacuated, an inert carrier gas, such as argon, and other gases flow into the chamber and the deposition begins. What gases? This depends on the layer that is to deposited. One method of depositing silica, for example, is to flow in ozone and an organic material containing silicon, such as tetraethylorthosilicate. The latter material is called a precursor. At the right temperature, the precursor decomposes and, with the help of ozone, a silica layer is formed.

One feature of CVD—the simultaneous coating of all surfaces of the substrate—may be viewed as either an advantage or a disadvantage. This is an advantage when optical domes are coated and a disadvantage when only one surface is to receive the multilayer. A disadvantage of CVD is that the equipment is usually purchased from the purveyors to the semiconductor industry and usually needs to be modified to improve its thickness uniformity. Another disadvantage is that the coatings manifest a mechanical stress, which in turn, may limit the thickness. Notwithstanding, there are at least two companies in the U.S. that produce optical coatings using CVD.

Pulsed plasma chemical vapor deposition

A plasma is a gas containing nearly equal concentrations of electrons and positive ions. At the risk of over simplification, the gas discharge region of a neon sign contains a plasma. In the plasma CVD process,[5] the gases admitted to the reaction chamber are similar to those of CVD mentioned above. It is an intense pulse of microwave power, however, that causes the precursor to decompose, react with the oxygen, and deposit a thin layer of material such as silica or titania. A layer of prescribed thickness is obtained after repeated pulses. The advantage of the plasma CVD process is that strange geometries may be coated, such as the inside of a tube[6] or interior of an MR-16 reflector. The plasma CVD reactors that the author is familiar with have been home built.

Future directions

Another advance has been in the software for the analysis of coatings. In 1956, for example, there was only one computer code in the U.S. that could analyze an optical coating and adjust the layer thicknesses to improve its performance. The personal computer and proliferation of software of the late 1980s has produced thousands of copies of codes that do the same job—but much better!

The discussion above makes it clear that there are advances into new technologies—into new methods of producing them. Most of the CVD and plasma CVD technology has concentrated on the deposition of oxide compounds. In the future, it is possible that CVD machinery will be developed to deposit coatings containing halogen and chalcagenide compounds, especially for the infrared.

Acknowledgment
All figures are from the book *Optical Coating Technology* and used with permission.

Glossary

Amplitude (of a light wave): Instantaneous value of the electric field strength.

Bell jar: Enclosure in which an optical coating is deposited.

Chemical vapor deposition (CVD): A method of producing optical coating.

Dichroic: Coatings that function at nonnormal incidence. They reflect and transmit complimentary colors.

Dielectric: As in *dielectric* multilayer. The layers are essentially nonabsorbing.

MR-16: A glass parabolic reflector of 51 mm diameter used in lighting.

Multilayer: Generic term for an optical coating.

Optical thickness: Arithmetic product of the physical thickness and refractive index.

Precursor: A gaseous chemical that is reacted to form a solid in a CVD.

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Philip Baumeister is a consultant dwelling in the bucolic rural solitude of Sebastopol, Calif. He would be delighted to unleash the awesome might of his 90 MHz Pentium to solve your coating design problems. Like so many other Pentiums, his has been rejuvenated with a brain transplant.

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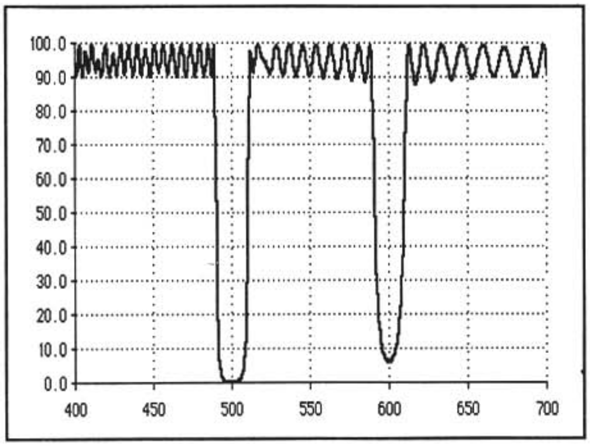

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