Advanced Optical Coatings Enable Energy-Efficient Lighting

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Worldwide electricity demand increased dramatically over the last 20 years, and demand is forecasted to double over the next 20. Factors contributing to this growth include an expanding global population, continued growth in the Asian economy, and even climate change (global warming). Scientists predict severe consequences if this demand for electricity is not curtailed.

According to the International Energy Agency, lighting accounts for 19% of worldwide electricity consumption. In the United States alone, lighting consumes 750 terawatt hours of energy and releases 1 trillion pounds of carbon dioxide into the atmosphere each year. Of those annual U.S. totals, 300 terawatt hours of electricity and 500 billion pounds of carbon dioxide gas can be directly attributed to home lighting.

There is no question that lighting is a major consumer of electricity, and more efficient lighting is needed to preserve our quality of life in the years ahead. Conventional wisdom may assert that compact fluorescent lamps (CFLs) are the best alternative to inefficient incandescent lamps, and technologists may believe that the light-emitting diode (LED) will ultimately replace the incandescent. However, the CFL does have its detractors, mainly because of the following factors: CFLs appear to have low light output, they are incompatible with many household fixtures, they have a tendency to fail early due to heat buildup that occurs when used in multiple socket fixtures, and they contain toxic mercury. As for LEDs, cost-effective LED lights that can retrofit into existing fixtures are still a long way off.

Energy-efficient halogen lamps offer an alternative approach to home lighting. The key to energy-efficient halogen is a hot-mirror coating that allows wasted heat produced by the filament of a halogen lamp to be recycled, thus reducing the amount of electricity required to produce the desired light output. This article examines the use of optical coatings to achieve this goal.

Halogen Lighting

Energy-efficient halogen lamps combine halogen lamp technology with an infrared reflecting coating to achieve improved electrical efficiency without giving up any of incandescent lighting's advantages, such as light quality, light output, dimming, availability for a wide variety of sockets, and no hazardous waste.

Conventional incandescent light sources are very inefficient; only a small portion of the electrical power they draw is converted into visible light. For example, *Figure 1* shows the theoretical output radiance for a 3000 kelvin (K) color temperature source, such as a tungsten bulb, as a function of wavelength. The narrow band of wavelengths visible to the human eye, from blue (400 nm) to red (700 nm), is highlighted in the graph. Immediately obvious in this graph is that the peak emission from a source at this color temperature is far outside the visible spectrum, and therefore the bulk of the energy output from such a source is invisible. Most of the output from this source occurs in the infrared spectral region. The human body senses infrared radiation as heat. Ideally, we would like to convert the infrared (heat) radiation into useful visible light.

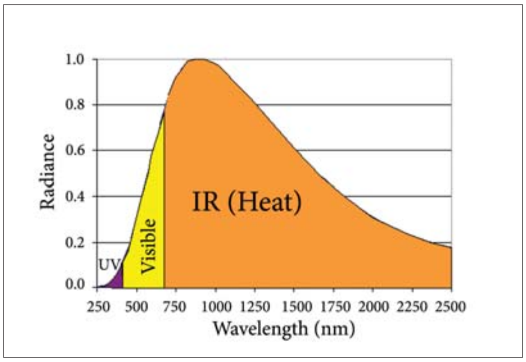

Figure 1: This graph shows the theoretical output radiance for a 3000 kelvin (K) color temperature source, such as a tungsten bulb, as a function of wavelength.

Optical Coatings

Practical optical coatings consist of many very thin layers, of varying thicknesses. This complexity allows them to reflect efficiently and selectively at a range of wavelengths, as well as function at a range of incidence angles.

Multilayer coatings can be designed to alter the reflecting characteristics of the substrate to produce anti-reflection, high reflection, spectral selectivity, and polarization sensitivity. For example, *Figure 2* shows a schematic of a hot mirror coating that separates the infrared energy from the visible light produced by the source by reflecting the infrared energy and transmitting the visible light.

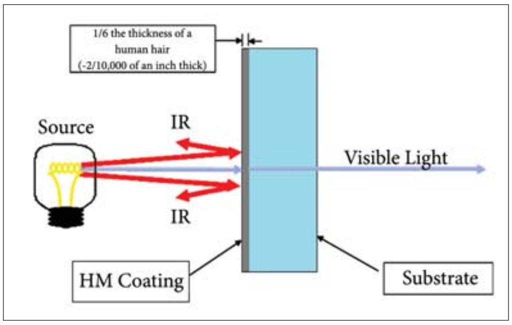

Figure 2: A hot mirror coating separates the infrared energy from the visible light produced by the source by reflecting the infrared energy and transmitting the visible light.

Optical coatings are conceptually simple to understand and, thanks to modern software, easy to design. However, manufacturing them is as much an art as a science. To achieve the desired result, it is necessary to control precisely the layer thickness and material indices of refraction. Given that layer thicknesses are typically less than an eighth of a micrometer and that minute changes in material microstructure can influence refractive index, this is not simple to accomplish, especially on a production basis. Critically important for this heat control application is the ability of the coating itself to withstand the high heat loads without failure. Good adhesion and layer integrity are also important if the optical coating is to be environmentally durable.

Designs and processes have been developed to efficiently and effectively apply hot mirror technology to the filament envelopes of a variety of lamp types, including single- and double-ended halogen lamps. In this case, a hot mirror coating is deposited directly on the glass or quartz envelope of the bulb. With a hot-mirror coating applied to a roughly spherical bulb with a well-centered filament, a portion of the infrared output is directed right back onto the filament and doesn't escape the bulb. The infrared light, which is focused back onto the filament, acts as another energy source for heating it up. The result is that less electricity is required to bring the bulb up to a given operating temperature. As such, this approach provides the dual benefit of eliminating heat right from the beginning of the system and yielding a more energy-efficient source.

Producing bulbs with these coatings requires close cooperation between the lamp manufacturer and the supplier of coating services and/or coating equipment. Bulb envelope shape; filament size, placement, and shape; and coating design must all be optimized to work together.

Figure 3 shows the spectral performance of a two-material, 47-layer hot mirror (HM) coating superimposed on the radiance curve shown in *Figure 1*. As seen in *Figure 3*, the two-material, 47-layer coating suppresses higher order reflection bands, thereby providing high transmission through the visible region of the spectrum, high reflection out to two microns, and necessary manufacturing tolerances.

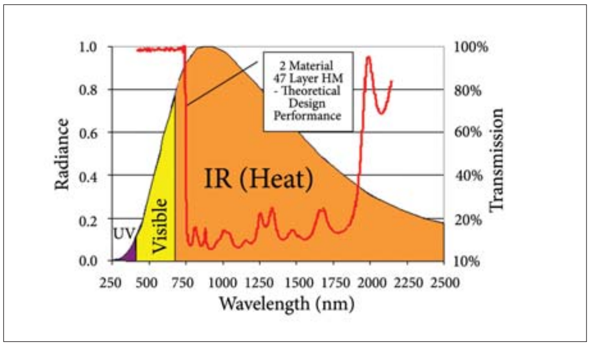

Figure 3: In this graph, the spectral performance of a two-material, 47-layer hot mirror coating is superimposed on the radiance curve shown in Figure 1.

The problems of thickness control, adhesion, stress in the coating, and temperature stability are compounded when trying to apply hot mirror coatings to the filament envelopes of halogen lamps. Having these coatings perform to specification over the rated lifetime of the lamp, which can be thousands of hours, is especially challenging.

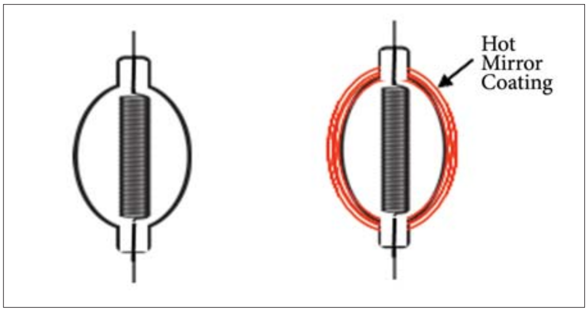

Figure 4: A double-ended halogen lamp is shown with and without a hot mirror coating.

Figure 4 shows a cross section of a typical double-ended halogen lamp before and after coating. The filament envelopes of these lamps are small (less than ½ inch in diameter), roughly spherical in shape, and, in the case of quartz lamps, operate at temperatures approaching 800° C for at least 3,000 hours.

Figure 5 shows an energy-efficient halogen lamp that consists of a halogen lamp capsule encased in the outer globe of a conventional incandescent bulb.

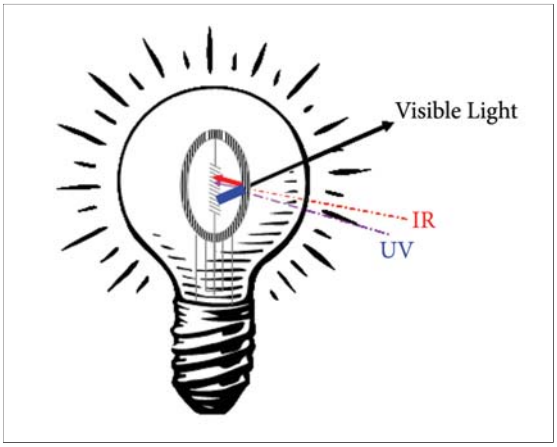

Figure 5: This energy-efficient halogen lamp (~25 to 30 lumens/watt) consists of a halogen lamp capsule encased in the outer globe of a conventional incandescent bulb.

Optical Thin-Film Coating Deposition Systems

There are several methodologies for producing thin film optical coatings, but only three techniques have proven successful for applying high-performance hot mirror coatings to the filament envelopes of lamps in volume production: low-pressure chemical vapor deposition (LPCVD), plasma impulse chemical vapor deposition (PICVD), and sputtering.

Low-Pressure Chemical Vapor Deposition (LPCVD)

In LPCVD, the coating material is created through a chemical reaction. Specifically, the parts to be coated are put into an evacuated chamber called the reactor and are heated to a temperature sufficient to drive a surface chemical reaction. This temperature is typically above 400° C. The reactor is filled with a chemical vapor, and all exposed parts of the substrate are uniformly coated. LPCVD is particularly useful for coating lamps because the lamp doesn't have to be rotated about its own axis during coating.

Hot mirror coatings deposited on lamp burners by LPCVD typically consist of tantalum pentoxide and silicon dioxide coating materials. In general, these materials are hard and durable, and they have good heat handling characteristics. They also tend to be highly stressed, which can be addressed somewhat by annealing immediately after coating, but even with annealing the physical thickness of coatings deposited by this method may be limited.

LPCVD production equipment is typically a large reactor that batch processes thousands of lamps in a single coating cycle.

Plasma Impulse Chemical Vapor Deposition (PICVD)

In PICVD, the lamps to be coated are placed inside a coating chamber and evacuated to the appropriate pressure. The chamber is then flooded with gaseous coating material precursors. By applying energy in the form of microwaves, a plasma is generated that decomposes the precursors into silicon or titanium, depending on the gas used, which are then oxidized to form a stable oxide coating layer on the surface of the lamps. Reaction products are swept out of the chamber during the "off" period. When the plasma is ignited again, the chamber is full of the pure coating gas. This leads to fast coating times and a homogeneous coating, as depletion of the coating gas close to the lamp surface is avoided. The gas composition can also be quickly changed. Thus, the overall coating is built up in small steps with each pulse, leading to a dense and homogeneous coating. The entire process can be monitored in a number of ways, ensuring precise control of the process and consistency in the coating quality.

Hot mirror coatings deposited on lamps by PICVD consist of titanium dioxide and silicon dioxide coating materials. In general, these materials are hard and durable, but have been known to fail when exposed to temperatures above 550° C for prolonged periods of time. PICVD, like LPCVD, has the advantage of not requiring that the lamp be rotated about its own axis during coating. PICVD coating chambers are very small, holding only a few lamps at a time. High-volume production requires many parallel chambers.

Sputtering

Sputtering is typically performed in a large cylindrical chamber, where the sputtering targets (coating materials) are arranged around the periphery, and the lamps to be coated are held on a rotating drum concentric with the chamber.

In action, the chamber is first evacuated and then filled with a low-pressure inert gas such as argon. A voltage is applied to the coating material target(s) (usually a metal or semiconductor), which ionizes the gas in the region around the target, forming a plasma. Ions from the plasma are accelerated into the target, causing atoms to sputter off the target material. These atoms then fill the chamber, and some are deposited on the surface of the lamps. Due to the presence of the low-pressure gas, the movement of the sputtered atoms is partially randomized, causing uniform coating, even over the highly curved surfaces of lamps.

If a small amount of oxygen is introduced into the machine during this process, sputtered material atoms will react with it, depositing oxides on the lamps. The process, called reactive sputtering, allows for the production of multilayer oxide coatings having excellent mechanical and thermal characteristics.

A unique approach to reactive sputtering, called MicroDyn®, has been developed. In MicroDyn, sputtering is augmented by a microwave plasma that forms a wider range of highly reactive oxygen species (ozone, etc.) to enhance the reaction process.

In all sputtering techniques, the sputtered target atoms come out with a large amount of energy, leading to inherently hard coatings. Due to the low stresses associated with sputtered coatings, multilayer coatings as thick as 100 micrometers have successfully been produced by this deposition technology.

MicroDyn sputtering, unlike LPCVD and PICVD, can deposit a wide variety of materials including alloys and a graded index of refraction materials. The process is very stable, and this allows the thickness of the vast majority of coatings deposited by this method to be controlled by time. A disadvantage of MicroDyn sputtering versus LPCVD and PICVD for coating lamps is that the lamps must be rotated about their own axis during coating in order to achieve required coating uniformity over the entire surface of the lamp.

Figure 6 is a picture of a MicroDyn sputtering machine. This is a fully automated machine that has two doors, four 40-inch cathodes, two microwave plasma sources, and a blanked-off port that is available for mounting a fifth cathode, heaters, diagnostics, etc.

Figure 6: The Model 67242 MicroDyn® sputtering machine is a fully automated machine with two doors, four 40-inch cathodes, two microwave plasma sources, and a blanked-off port that is available for mounting a fifth cathode, heaters, diagnostics, etc.

Figure 7 is a picture of a MicroDyn machine with a fully loaded drum of halogen lamps that are ready for coating.

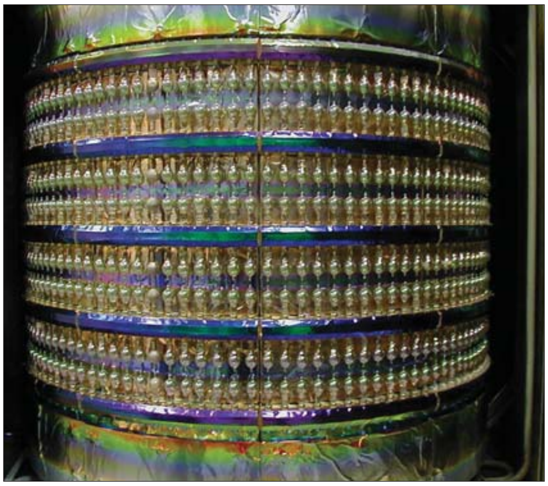

Figure 7: A MicroDyn sputtering machine is shown loaded with halogen lamps.

Conclusion

The energy-efficient halogen lamp will soon be available for the home. This new, low-cost lighting technology offers many important advantages: consumers and end users benefit from its energy savings and its complete compatibility with existing home fixtures, the environment benefits from its lower energy usage and lack of hazardous waste, and business benefits from higher stakeholder satisfaction and loyalty.

However, significant effort and sacrifice will be required to realize these gains. The lighting industry has to replace old lighting technology with this new technology. Consumers and users must be made aware of its benefits. And new financing and energy pricing initiatives need to be developed to help remove the largest barrier to the availability and use of this new lamp – the higher initial investment and production costs.

About The Author

Lee Bartolomei is the founder of Deposition Sciences, Inc. (DSI) and has served as the company's president, CEO, and chairman of the board since its inception in 1985. Bartolomei earned his BSME from the University of California, Berkeley in 1962, and his MBA from the University of Santa Clara in 1966. He holds several patents for precision optical coatings, optical components, and coating deposition processes. ●