

Coating Technologies for High-Damage-Threshold Optics

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Fig. 1 Thin-film dielectric coatings are found on a variety of optics—including mirrors, filters, lenses, etalons, polarizing and beamsplitting optics.

In nearly all of today's optical systems—from the simplest to the most complex—optical thin films play a critical role. They tailor the reflective, transmissive, polarizing and dispersive properties of the optics, and greatly influence the overall performance of optical systems and instruments.

In high-power applications, thin-film dielectric coatings are especially important because they are often the limiting factor driving performance. Historically, large laser systems used in the military, laser fusion and industrial welding and cutting have dominated the high-power industry. Today, however, many high-power applications use small laser systems, such as those found in medical instruments, manufacturing equipment, scientific instruments, advanced displays and remote-sensing systems.

Many of these systems are based on nonlinear optical technology that requires high peak powers to maximize frequency conversion. Other systems, such as those used in the semiconductor industry for repair and testing, need high power to produce localized microscopic heating or cutting. The optics used in all these laser systems

require low losses, high efficiency, low absorption, precise spectral optical properties and high laser damage thresholds.

Coatings Key to High Damage Thresholds

Many factors influence laser damage in optics. One of the most common causes of catastrophic failure is the absorption of energy through gross defect sites on the coating itself. Thus, surface preparation (including polishing) and coating quality are major factors that limit performance. Energy absorption generates heat that causes localized melting, thermal stress fractures, or, if sufficient heat is generated, a small explosion that ablates the coating.

To minimize defect sites and contaminants and thereby achieve high damage thresholds, manufacturers must ensure clean practices throughout the fabrication and coating of the optic, choose appropriate thin-film materials, and maintain tight control of the process parameters. Careful substrate polishing is also important because surface roughness and quality (surface figure and irregularity) affect the damage threshold. Sophisticated polishing techniques, including super-polishing, can substantially improve the damage threshold by reducing scatter and absorptive losses.

Damage threshold is measured in W/cm^2 for continuous wave applications, and J/cm^2 in a given pulse duration for pulsed applications. For both, spot size is important. In some instances, high damage thresholds can be achieved for very small spot sizes because the thermal diffusion length is very small and the surrounding substrate acts as an effective heat sink.

For pulsed lasers, understanding the data can be very difficult. Measurement protocols

can differ widely from laboratory to laboratory due to the many parameters involved including the physical parameters such as pulse length, beam spot size, pulse repetition rate, but also procedural issues such as cleaning procedure, method of determining damage, exposure pattern and number of spots irradiated. The best method is to measure a statistically significant sample size using a well-calibrated measurement setup. The International Standards Organization (ISO) has developed standards to normalize damage threshold measurements (ISO-11254-1:2000 and ISO-11254-2:2001). To get the most meaningful results, you must take into account the specific application, including wavelength and laser performance specifications.

Today's Coating Revolution

The telecom boom of the late 1990s helped drive a revolution in dielectric thin-film technology, especially for applications in the visible and near-infrared. Dense wavelength-division-multiplexed optical communications systems require low loss, high spectral performance and thin-film filters that can withstand the environmental challenges of humidity and thermal stress. These filters are one of the key components enabling the deployment of low-cost fiber-optic systems.

Before the boom, manufacturers did not have the thin-film technology required to make these complex filters, which require hundreds of layers; state-of-the-art systems were typically limited to about 50 layers. Since then, however, newer deposition techniques, such as ion-beam sputtering and ion-assisted deposition systems, were developed and perfected to fabricate the coatings. These systems offer a high degree of control, high uniformity and the deposition of hard oxide materials that provide rigorous environmental durability.

These coatings are "non-shifting" when exposed to humidity and can operate over a wide temperature range and humidity

conditions without failure. Because they are denser and more uniform with fewer defects, they can also result in high laser damage thresholds.

A Comparison of E-beam, IAD and IBS

The three most commonly used technologies for depositing multi-layer high-damage-threshold dielectric thin-film coatings are electron-beam deposition (e-beam), ion-assisted e-beam (IAD) and ion-beam sputtering (IBS). All are performed in a vacuum chamber, and, for all, the evaporated materials, deposition energy, and process parameters—such as residual and partial gas pressures, deposition rate and substrate temperature—affect the film properties.

The main difference between the three processes is in the deposition energies. Because of this variation, the film properties differ markedly between the processes—even for the same material. If the deposited atoms have low energy or mobility, the film will contain microvoids or pores. These voids create a lower packing density (the ratio of the volume of the solid part of the film to the film's total volume) that results in a less dense film.

Materials with lower packing densities have lower refractive indices than bulk. Typical film packing densities are in the range of 0.75 to 1.05, with most falling between 0.85 to 1.02. Higher-than-unity packing densities result in high internal stresses, especially for high-index coating materials.

Less dense films—that is, those with microvoids—are less stable environmentally. When the film is exposed to humidity, these microvoids eventually fill up with water. Thus, the film's refractive index increases with humidity—a phenomenon referred to as "environmental shifting." A film with spectral properties that do not change with humidity is called "non-shifting."

Manufacturers strive to perform coatings at higher energies (i.e., heating of the substrate, or using a high-energy deposition

process) so that the molecules have higher mobility during the condensation at the substrate surface, resulting in the more ideal higher packing densities.

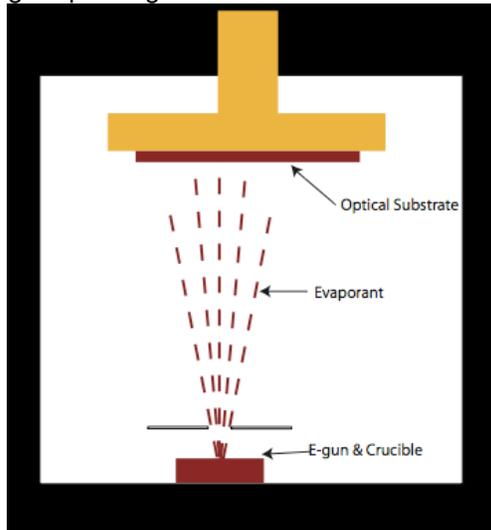


Fig. 2 Title: Electron-beam deposition
Caption: Electron-beam deposition is the most common coating technology. It can be used to deposit a wide variety of materials.

Electron-beam deposition, the most common coating technology, is the most versatile and least expensive of the three. With this technique, an electron beam generated from a hot filament is focused via a magnetic field onto a copper hearth that is filled with the material to be evaporated, typically a metal oxide or fluoride [Fig 2]. The electron beam heats the material, causing it to evaporate and condense on all surfaces inside the vacuum chamber that are in a direct line of sight.

Typically, a rotating substrate holder keeps the substrate in a horizontal plane, and a shutter is used to stop the deposition when the desired film thickness is achieved. Because the energies of the deposited atoms are low, typically around 0.1 eV, the substrate is heated to a temperature of 150° to 300° C. This helps the nucleation of the material, creating a denser film.

Overall, e-beam deposition results in porous films that do not have a high packing

density. A surface roughness of 10 Å rms is typical for a 500-nm high reflector. Published laser damage threshold specifications from various manufacturers are typically between 20-40 J/cm² at 1.064 μm in a 20-ns pulse at 20-Hz repetition rates.

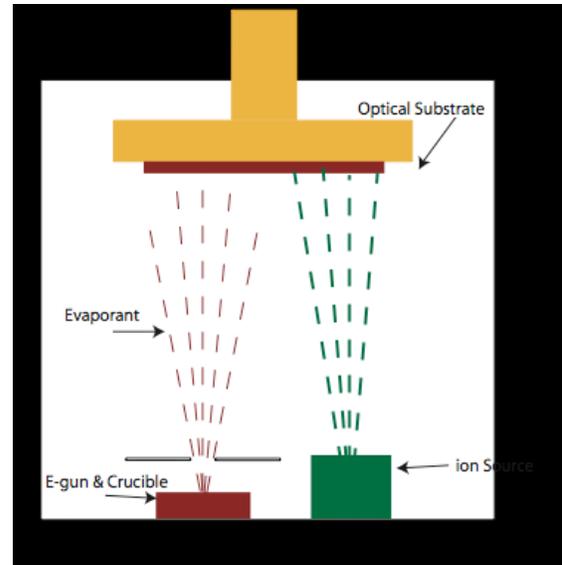


Fig. 3 Title: Ion-assisted deposition
Caption: Ion-assisted deposition uses an ion source to increase the activation energy of the deposited material, resulting in denser, more uniform films.

Ion-assisted e-beam deposition is similar to e-beam deposition with the addition of an ion gun [Fig. 3]. The ion gun bombards the substrate surface with a flux of high-energy ions composed of oxygen and/or argon gas. The bombardment by this energetic beam is similar to atomic shot peening, which helps to produce denser films.

The main advantage of IAD is this increase in kinetic energy of the deposited molecules, resulting in higher packing density of the films. Unlike low-density e-beam films, IAD films are of medium density. Another advantage of IAD is that the substrates can be kept at or near room temperatures, allowing for a variety of substrates, including plastic ones.

A drawback is that IAD cannot easily be used with fluorides. For one reason, the fluorine can disassociate. For another, there is no easy method for avoiding contamination. IAD films typically can achieve a surface roughness of 4 Å rms. Typical laser damage thresholds for IAD films are slightly less than those of e-beam films.

With the third technique, ion-beam sputtering, an ion beam from an ion source irradiates a metal or metal oxide target [Fig 4]. If the ions have sufficient energy, they dislodge—sputter—material, atom by atom, from the surface of the target. The material is then deposited on the substrate.

The sputtered molecules have significantly more energy, about 10 eV, or 100 times the thermal energy in an e-beam. The energy is so high that the molecules form covalent bonds upon deposition. The resulting films are uniform, dense and non-porous, and have superior adhesion.

Due to the high packing density, the refractive index of IBS films is near the bulk value, and the films are practically impervious to water vapor (thus, they are non-shifting). Surface roughness of a 50-layer film can be less than 1 Å rms. Moreover, because IBS is a sputter process rather than a thermal evaporative process, it is more repeatable and controllable, and can easily be automated.

On the other hand, the atom-by-atom removal of material is a slower and more expensive technique. Not only is the equipment more expensive, but so are the maintenance and materials. IBS is also less flexible, and harder to scale to large substrates. Like IAD, fluorides cannot be sputtered easily because the fluorine dissociates in the sputtering process. This limits the use of IBS coatings at UV wavelengths, although $\text{HfO}_2/\text{SiO}_2$ coatings can be used down to approximately 250 nm.

IBS was first developed for inertial navigation equipment, specifically laser ring

gyros, in the 1970s. IBS films are ideal for laser ring gyros because of their low scatter and absorptive properties, and because the films are environmentally stable. During the telecom boom, IBS was used to coat the ends of fibers as well as DWDM filters. This coating technology has evolved significantly so that larger components now can be coated with sophisticated and complex designs, including high-damage-threshold optics.

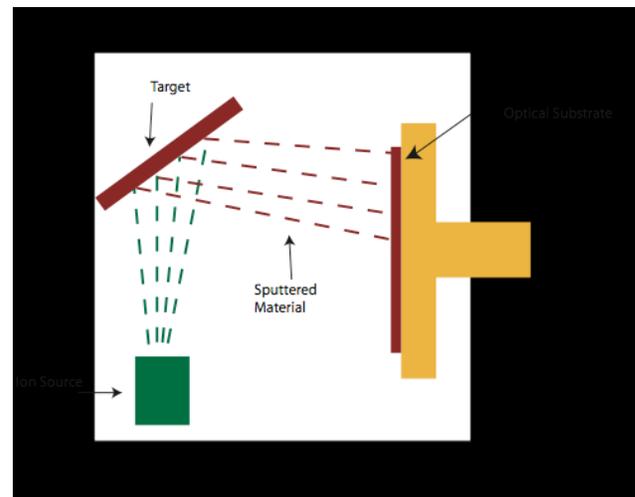


Figure 4: Title: Ion Beam Sputtering
Caption: The IBS process offers a high degree of control. Here an ion beam is used to sputter atoms off a target.

Theoretically, IBS should offer higher damage thresholds because the films are near the theoretical limits of reflectance, low absorption and bulk refractive indices. Recently, IBS films have proven to offer comparable damage thresholds to those of conventional e-beam coatings, which for a high-reflector coating can be as high as 40 J/cm^2 at 1.064 μm in a 20-ns pulse.

A Word on Flatness after Coating

Stress is a well-known problem in thin-film optical coatings. The biggest concern is usually deformation of the coated substrate. Historically, coating vendors have often dealt with this by only specifying surface figure of the substrates prior to coating.

Since the main effect of coating stress is the introduction of power to the surface, the effect can be compensated for in many applications by a slight focusing of the optical system. The use of thick substrates can reduce this deformation because the deformation is a function of the square of the ratio between the diameter and thickness of the substrates.

Designing coatings that balance internal stresses is possible but difficult. In e-beam coatings, such stresses in the layers are typically on the order of 100 MegaPascals (MPa). Stress varies with deposition conditions and can be both tensile and compressive. It is also dependent on environmental factors. Internal stresses can result in a mirror that bends back and forth with humidity, for example. An e-beam coating typically takes between three and four weeks to stabilize after the coating comes out of the deposition chamber.

By contrast, IBS introduces more stress initially—up to 500 MPa—but the internal stresses are stable with time because of the non-porous nature of the films. Thus, additional coatings can be applied to the second side of the optic during manufacturing to compensate for the stress. This has resulted in mirrors with better than $\lambda/10$ surface flatness that are independent of environmental factors. IAD coatings have stress and environmental sensitivity properties that are between those of e-beam and IBS coatings.

Advances in dielectric thin-film coating technology that resulted from the telecom sector have provided more choices for high-damage-threshold optics for the visible and near-infrared. E-beam deposition is the most versatile, least expensive and most easily scalable of the processes.

However, because the process is a relatively low-energy one, the films are porous and environmentally less stable than IBS or IAB, both of which generate higher density films. IBS is more expensive, but the density and

stability of IBS thin films help offset the increased cost and manufacturing limitations for some applications.

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