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Future Trends in Optical Coatings for High-Power Laser Applications

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ABSTRACT

Inertial Confinement Fusion (ICF) research has historically been a driver in the development of high performance, high damage threshold optical coatings. This is particularly the case now as the ICF community develops plans for a proposed 1.8 mega-joule solid state (Nd^{+3} -phosphate glass) laser system. The new system, the National Ignition Facility, is possible in part due to advances in optical coatings technology including the laser-conditioning of multilayer dielectrics and broadened applications for room-temperature deposited coatings. Sol-gel AR coatings are the standard for large, high-power laser optics and sol-gel HR coatings are being developed. For mirror and polarizer coatings, e-beam-deposited dielectrics continue to provide the highest damage threshold coatings, but their laser damage thresholds and optical performance are limited by μm -scale defects and poor control over layer thickness, respectively. More energetic deposition techniques such as IAD and IBS, now popular in the commercial market, offer both advantages and disadvantages in this high-damage-threshold coatings market.

Keywords: laser damage, defects, optical coatings, optical monitors, e-beam deposition, sol-gel, evaporant distribution.

1. INTRODUCTION

The need for mirrors, polarizers and antireflection coatings for high power lasers has been one of the driving forces for advances in the design, production and use of optical coatings over the last two decades. This trend should continue as the Inertial Confinement Fusion (ICF) community plans for the construction of the next generation ICF laser. This laser, called the National Ignition Facility (NIF), will be a Nd:glass laser, as is the present Nova laser at LLNL. The NIF is designed to supply 1.8 MJ of 351 nm light per pulse in order to achieve ignition of the deuterium-tritium fuel pellets. In the present design the system will consist of 192 square beams of 40-cm aperture. This laser will include over 7,500 full-aperture optics, including 1,182 mirrors and 192 polarizers.

A scientific prototype of a single beam of the multipass NIF laser architecture is presently being tested at LLNL. This laser, called Beamlet, has to date demonstrated a 12 kJ output at 1.053 μm and 3 ns. The peak-to-average fluence ratio is only 1.2/1 over the 35 cm beam aperture.

The optical coatings needed for the NIF laser present several interesting challenges. Listed below, in decreasing order of importance, are the most important properties of optical coatings used for ICF applications.

Optical Coating properties:

- Laser damage threshold (low defects)
- Spectral performance (uniformity, thickness control)
- Coating stress (causes wavefront error)
- Environmental stability (spectral and stress)
- Mechanical stability

Because priorities are different for most other applications, choices of deposition process and materials often differ. Presently, e-beam deposited $\text{HfO}_2/\text{SiO}_2$ coatings are the multilayers of choice for high damage threshold applications near $1.06\text{ }\mu\text{m}$. HfO_2 is inherently difficult to deposit because of its high melting point ($\sim 2200^\circ\text{C}$) as well as the solid state phase transformations it undergoes while being heated ($\sim 1700^\circ\text{C}$). It is, therefore, not the material of choice for most commercial optics applications. Also for many coatings applications e-beam deposition has been replaced by energetic deposition processes such as ion-assisted deposition (IAD) and ion-beam sputtering (IBS), which produce hard dense coatings. Unfortunately, these energetic techniques have been slow to show damage thresholds as high as those provided by conventional e-beam evaporation. Similar differences exist for AR coatings where soft, porous sol-gel coatings are the materials of choice for large aperture, high fluence applications. For other applications where environmental and mechanical (abrasion resistance, etc.) stability are priorities, physical vapor deposited (PVD) AR coatings are preferred. Sol-gel HR coatings are now also being developed and will be used for low-fluence cavity HRs on the NIF.

This paper discusses the advantages and limitations resulting from the material and deposition technique choices made for high damage threshold coatings. Areas of needed development for both sol-gel and e-beam coatings are emphasized. Also discussed is the growing potential for other deposition processes to find application in the high fluence arena.

2. MULTILAYER E-BEAM COATINGS

The two most challenging issues for ICF mirrors and polarizers are damage threshold and optical performance. For e-beam deposited hafnia-silica these issues are associated with two important limitations of the evaporation process (Fig. 1), particle ejection and evaporant distribution transients. These two phenomena result in coating defects and poor layer thickness control, respectively. The following paragraphs discuss directions being pursued to alleviate these problems.

2.1 Laser damage threshold

As has been discussed extensively in the literature, the laser damage in multilayer coatings is typically a localized phenomenon initiated at μm -scale nodular defects in the coatings.^[1] The defects grow due to self-shadowing effects initiated at seed particles either present on the substrate or deposited during the coating process. When state-of-the-art vacuum and substrate cleaning technology is used, defect seeds caused by

Figure 1. Drawing showing particulates and transient evaporant distributions resulting from poor control over the e-beam evaporation process.

chamber or substrate contamination should not be present. This, however, still leaves the deposition process itself as the major source of defect seeds. For $\text{HfO}_2/\text{SiO}_2$, for example, the defect seeds may be due to splashing of molten material from the melt or to cracking resulting from thermally-induced phase transitions in the material.

If the damage thresholds of e-beam $\text{HfO}_2/\text{SiO}_2$ coatings are to be increased and made more consistent, as required for the NIF, better control over the evaporation process is needed. Such progress will require improved in-situ monitoring techniques to characterize particulate-causing events and then improved e-gun technology (more uniform beams, better sweep control, etc.) to prevent such events. Understanding the sources of defect seeds is a challenge not only for e-beam coatings but also for coatings deposited using energetic techniques such as IAD or IBS which also have defect-driven damage thresholds. Another paper in this symposium discusses progress in the area of defect characterization using atomic force microscopy (AFM) and focused ion-beam (FIB) cross-sectioning.^[2]

Until techniques are developed to eliminate coating defects we will have to settle for minimizing the defect's influence on the damage threshold of the coatings. This is presently done using the technique of laser conditioning, a process by which the damage threshold of the optic is increased by typically a factor of 2 or 3 as a result of previous illumination of the optic at lower fluences.^[3] Laser conditioning has been associated with the removal or stabilization of nodular defects.^[1]

The designs of the Beamlet and NIF lasers are based on laser-conditioned damage thresholds for mirrors and polarizers. The first large-aperture laser-conditioned optics are presently in use on the Beamlet laser. These 40 cm x 75 cm polarizer coatings were laser conditioned by rastering the sample in front of the beam of a damage test laser at 6 levels of increasing fluence ranging from half the unconditioned threshold up to the desired use fluence.^[4] Each scan took approximately 15 hrs. Further development is needed to reduce the high capital and production costs associated with this process. The ultimate goal, however, is to reduce the defect problem so that conditioning is no longer required.

2.2 Optical performance

While polarizers meeting NIF specifications were produced for the Beamlet laser, production yields of such coatings must be improved prior to NIF optics production. The most significant problem in depositing high performance coatings is good layer-to-layer thickness control. As the e-gun evaporates material, changes in the topography, composition, and structure of the source material cause the evaporant distribution to change with time. This causes material to be deposited on the substrates at different rates than is being observed on the monitoring devices, thus resulting in coatings with incorrect layer thicknesses. In some cases the time dependence of the evaporant distribution can be reduced by varying such parameters as crucible size and refilling rate.^[5] In order to characterize the evaporant distribution transients in their coating chamber, the Laboratory for Laser Energetics at the Univ. of Rochester has tracked the relative deposition rates at multiple quartz crystal monitor chips located across the chamber.^[6] This technique aided in the production of high performance polarizers for their Omega Upgrade laser.

Significant work has also been done in the area of optical monitoring. Broadband or multi-wavelength optical monitoring systems which monitor production substrates in transmission or reflection allows a spectral region which is very sensitive to layer thickness, but not important to coating use, to be used to determine when a layer is completed.^[7] In some cases broadband spectral characteristics can be evaluated using merit-function analysis and then the remaining layers can be redesigned to correct for errors. The use of these optical monitoring techniques have helped some deposition processes, such as IBS, to be significantly automated. Such automation requires good knowledge of index dispersion with good reproducibility of indices. Automation has been most successful with energetic processes which provide dense anisotropic materials. Automation is more difficult with e-beam deposited HfO_2 which has a structure that is very sensitive to deposition parameters and layer thickness.

3. SOL-GEL COATINGS

3.1 Anti-reflective Coatings

Sol-gel quarterwave AR coatings have been used on the Nova laser at LLNL and on other high-power fusion lasers throughout the world for about 10 years. These coatings are prepared from a colloidal suspension of 20 nm spherical silica particles in ethanol by either spin or dip coating. Evaporation of the ethanol at room temperature leaves a loosely packed layer of silica spheres which require no further processing. The loose packing of the spheres gives rise to porosity which lowers the refractive index to approximately 1.22. This is close to that required for quarterwave AR coatings of substrates of index in the range 1.45-1.50. This porosity also causes the coating to be soft and easily abraded but allows easy removal and recoating, when necessary, without refinishing the substrate.

While the optical properties are no better than the best multilayer coatings prepared by other methods, the laser damage threshold is much higher. This high threshold, together with ease of application, accounts for the preeminence of sol-gel AR coatings in the high power laser field. Ammonia treatment to increase abrasion resistance is the only recent modification to this system. This is fully described in another paper at this conference.^[8] It is unlikely that anything but very minor improvements will be made to the system in the future.

3.2 HR Coatings

Sol-gel HR coatings prepared by stacking alternating quarterwave layers of porous high and low index oxides have been under investigation for a number of years but are not yet widely used in practical application. These coatings are prepared from colloidal suspensions of oxides in a similar manner to the silica AR coatings described above. Colloidal silica has been used exclusively for the low index component and colloidal AlOOH , ZrO_2 and HfO_2 have been the preferred materials for the high index component. Stacked coatings of this type tend to be weak because of low particle-to-particle bond strength. This has contributed to low laser damage thresholds. Recently, organic polymer binders have been added to the colloidal suspensions and this has resulted in much stronger coatings with corresponding increase in damage threshold. This work is described in more detail in another paper at this conference.^[9] Initial application was carried out on a spin coater but more recently meniscus coating has proved to be particularly applicable for the preparation of the large square or rectangular mirrors required for the latest laser designs. At present 40 x 40 cm square mirrors have recently been fabricated that are expected to meet the specification for cavity mirrors in the Beamlet laser.

While sol-gel HR coatings have some advantages over coatings prepared by other methods, it is unlikely that they will attain the dominance of their AR counterparts. Their optical performance is restricted by some environmental instability brought about by the high surface area (due to porosity). Simple cavity mirrors and possibly turning mirrors are easily manufactured but more complex designs such as polarizers may be very difficult to produce. The laser damage threshold is, at best, equivalent to other materials. The principal advantages of sol-gel HRs are low production and capital equipment costs and the ability to re-coat the substrate without refinishing the optical surface. These advantages are greatest for large substrates.

4. ENERGETIC DEPOSITION PROCESSES

Because bulk materials tend to show the highest damage thresholds, it has been hoped that energetic deposition processes that provide bulk-like coatings should also provide high damage thresholds. This has not typically been the case, however, so e-beam continues to be the favored deposition method for high damage threshold optics. The role of two of the most popular energetic deposition processes, IAD and IBS, in the high damage threshold field have recently been reviewed.^[10, 11] The advantages offered by the IAD technique do not directly address the defect issue and the presence of the ion gun may even provide additional sources for contamination. IBS, in contrast, has been developed for laser gyro mirror applications requiring low scatter and, therefore, low defect counts. IBS is presently showing the most promise for high damage threshold applications. A significant challenge will be to scale the IBS technique to large apertures.

In general, these energetic deposition techniques have not been developed specifically for high damage threshold applications and the database from which conclusions in this area are being based is rather small. We must be careful not to give up on these techniques before they have been sufficiently studied.

5. SUMMARY:

New ICF laser systems continue to provide a driving force for the development of high damage threshold coatings. E-beam deposited $\text{HfO}_2/\text{SiO}_2$ coatings continue to be the coatings of choice for these applications, but significant challenges remain in decreasing the particulate and evaporant distribution transient problems. Ion-beam sputtering is showing promise for high fluence applications but the scaling issue remains

to be addressed. Sol-gel coatings are likely to remain the AR coatings of choice in ICF lasers. Future developments in the sol-gel area will be in the production of HR coatings.

6. ACKNOWLEDGMENTS

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