

## Studies Toward Improving the Laser Damage Resistance of UV Coatings

Authors: Samuel Pellicori and David Sanchez  
*Materion Coating Materials News*

The shift in laser wavelength to UV is accompanied by the need to increase the Laser Induced Damage Threshold (LIDT) of the HR (high-reflective) and AR (anti-reflective) coatings on the optics that direct and manipulate the beam. Many previous [Coating Materials News](#) articles have touched upon topics that help us understand the process in creating the high-performance films necessary to unleash the full potential of photonics in industry. This article will outline, discuss and begin a dialog on a key aspect of optical coating lifetime and LIDT. It will address the roles that different materials and processes play in increasing the durability of coatings in their work environment.

### Applications of Ultra Violet (UV) Lasers

Industrial applications of high-power lasers include welding, cutting and marking of various materials ranging from metals to polymers. The kW powers that were available until recently were provided by bulky CO<sub>2</sub> lasers at wavelength 10.6 μm. Since all metals reflect highly at this wavelength, power levels needed to be very high to be efficient. In addition, as lasers became increasingly popular for cutting and welding, stray laser light presented an extreme workplace hazard. These factors posed a strict demand on the coatings that were used to steer the laser beam and anti-reflect the lenses. These problems exist even at 1.06 μm, the wavelength of Nd:YAG lasers. There was a move to shorter wavelengths where material absorption was higher, thus increasing the efficiency of heating needed for welding and cutting. The third harmonic laser wavelength of Nd:YAG at 355 nm, and diode lasers with wavelengths <450 nm, have become the workhorses for the industry. Diode-pumped solid-state lasers are used for micro-machining, micro-lithography, micro-hole drilling, welding in micro-electronics and opto-electronic applications. In many cases, they replace the more expensive and exotic excimer lasers that operate at wavelengths below ~250 nm. High pulse repetition rates near 5 kHz are possible. Some applications require very high peak powers that only pulsed lasers can produce. Pulse widths in the nano-sec range are used.

UV lasers are especially effective for welding copper, aluminum and stainless steel. Copper is widely used to produce commercial electronic devices such as computers and cell phones. The high UV laser powers possible enable faster assembly than previously achievable. One reason for this is that the smaller wavelength permits concentration to a smaller spot-welding size.

### Resisting Damage by High-power Lasers: Damage Mechanisms & Deposition Processes

A key objective is to increase the resistance of coatings to laser induced damage (LID). Laser damage is generally defined as the fluence at which materials will first exhibit damage in the form of melting, excavation of material or mechanical stress.

Over a half-century, researchers have presented their studies at the [SPIE Boulder Damage Symposium](#), whose purpose is to disseminate the latest knowledge to the laser community with due emphasis on optical coatings. The fact that the Symposium has continued during the past 50 years attests to the ongoing complexity of the subject. The persistent goals in laser research fall into two categories: (1) identify and reduce the density of defects that pose limitations to LIDT and (2) understand the damage mechanisms such as pulse width and repetition rate for short pulse lasers and the effects of multiple shots on coating lifetime.

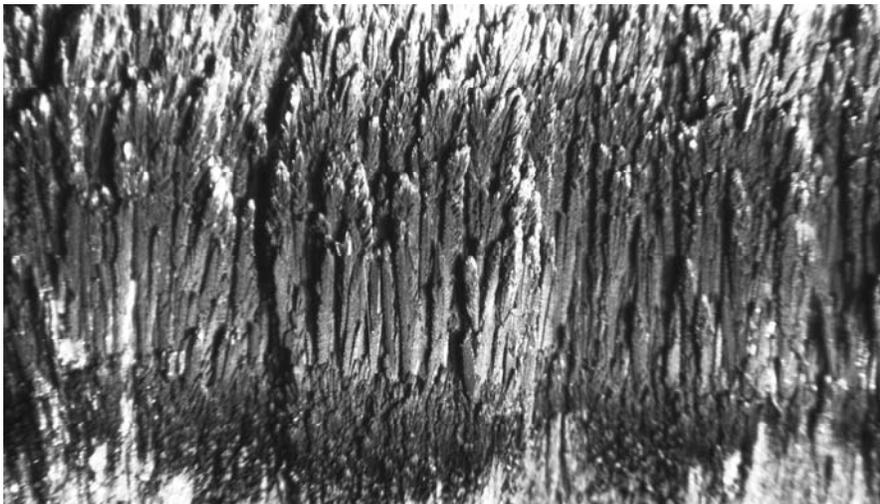
Further studies include optimizing material choices for the various wavelength applications and selecting the appropriate deposition process. The deposition process and its specific parameters are perhaps the most important considerations for increasing the laser induced damage threshold. Companion parameters consider substrate surface preparation and contamination avoidance. Applications for high peak-power lasers involving AR coatings require attention to the substrate surface polish and contamination issues where high electric field standing waves can reside. For high reflector (HR) applications, however, substrate roughness is the dominant factor because it influences film growth microstructure by moderating surface diffusion of both arriving and reacting species. The important issues to examine for AR coatings are coating absorption, defects and inclusions.

The coating's absorption capability plays a major role in how vulnerable the coating will be to damage under high powers and long pulse lengths. Nd-YAG lasers used in the third harmonic at 355 nm, and all UV laser coatings, are especially sensitive to film absorption; the small number of high-index materials available with the required low absorption complicates the problem. Oxide-compound coating materials with low absorption below 400 nm include:  $\text{HfO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Sc}_2\text{O}_3$ ,  $\text{Y}_2\text{O}_3$ ,  $\text{ZrO}_2$ . These materials are typically reactively sputter- or E-beam deposited. The deposition process employed is chosen to generally achieve a balance between incompletely oxidized compositions and microscopic particulate emanation and inclusion. The deposition process must produce stoichiometrically fully-oxidized compositions to avoid absorption. Oxide compound films, if not fully reacted with oxygen, can contain mixed sub-oxide states that absorb. Reactive evaporation and deposition by E-beam with IAD or Plasma assist produces highly oxidized films. Particulate production can be higher with E-Beam. Low particulate emission is characteristic of sputter deposition, but sputtered films can have higher absorption due to partial reduction or the inclusion of the working gas and higher stress. In the case of the fluoride compounds, a deposition process with excessive energy can result in decomposition, thereby inducing absorption. Fluoride compounds deposited by thermal evaporation are the only material option for use in laser applications at wavelengths shorter than  $\sim 250$  nm [1].

A detrimental contributor to low LIDT is the presence of defects on the surface or within the coating layers. These might result from microscopic particulate spatter, mostly associated with E-beam evaporation, as opposed to sputter deposition where larger flakes from shielding or chamber dominate. Defects can also be at the atomic/molecular level resulting from stoichiometric vacancies (increasing absorption), arcing or contamination sites. Nodules that grow from the particulate seeds are one of the major sources of low LIDT, especially for HRs used with multiple-shot short-pulsed lasers. Electric field concentration at these nodules produces explosive vaporization of material, and subsequent laser exposure results in the growth of the resulting damage site. Increases in LIDT have been the result of introducing oblique etching steps between layer growth cycles to reduce nodule size and population [2].

At the nano-structure scale, film morphology can be a factor. Amorphous film growth exhibits higher LIDT than coarse/columnar growth. High energies inherent to magnetron and ion-beam sputtering encourage amorphous microstructures but can induce compound reduction and stress. Increasing ion energy encourages amorphous morphology relative to laser damage resistance. The larger stress inherent in densely packed microstructures and/or compound reduction reactions can lead to absorption and facilitate dielectric breakdown. Therefore, the deposition process parameters need to be tuned to the materials used.

The control of film growth morphology was recently discussed in [Coating Materials News.\[3\]](#) Following, Figure 1 illustrates a cross-section of coarse growth structure of a 4 mm thick aluminum layer that had built up on a cold chamber wall after hundreds of coating cycles. The dendritic columns initiate at a “seed,” and as a result of poor mobility, the arriving Aluminum atoms then attach to low energy growth sites characteristic of low packing density.

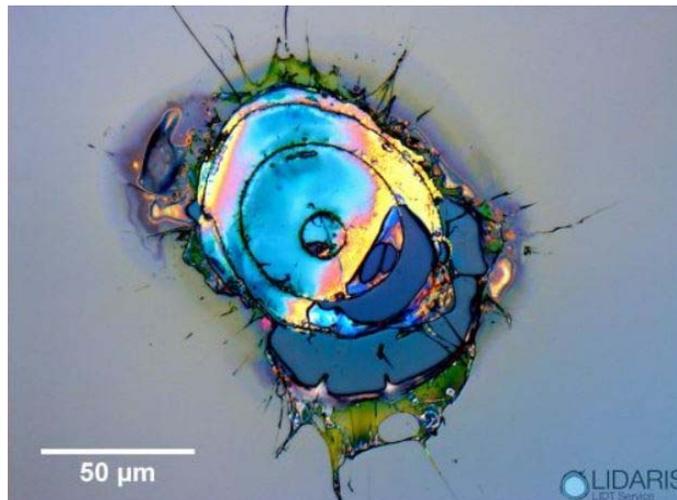


*Figure 1. Cross-section micro photo of a 4 mm thick aluminum layer that grew on the cold wall of a coating chamber after hundreds of deposition cycles. (Photo credit: S. Pellicori)*

### Coating Exposure Fatigue and Lifetime

Measured LIDT for high peak power applications is a function of the laser's power and exposure rate, the latter which encompasses pulse number and pulse-width. With continuous waveform (CW) lasers, heating and dielectric breakdown are damage mechanisms. Laser exposure to pulse-widths in the nano-sec range cause melting in coatings with low LIDT, while damage resulting at pulse-widths in the pico-sec range is in the form of vaporization (explosive plasma generation) with dielectric breakdown. LIDT is a function of the fluence level and the number of shots that a site receives before it exhibits damage that affects the function of the coating. This testing regime is referred to as "1-on-1" and "s-on-1", where s is the number of laser shots that a particular spot receives. The nature of the damage is influenced by the pulse number as well as the fluence level. This damage phenomenon is known as "incubation" or "fatigue," and in cases involving low fluence levels does not become significant until after dozens of shots are accumulated. The onset of fatigue occurs earlier when high fluences are irradiated. That becomes a problem for applications that require hundreds and thousands of shots which is typical in machining applications.

Approaches to increase the LIDT of 355 nm mirrors by reducing fatigue is a topic of study. Research is inspired by the observation that the LIDT for a single-shot is different than that for multiple-shots [4].



*Figure 2. The appearance of this damage image suggests that at least three particulate defects were initiation sites for deep damage that spread to a larger melted area. (Photo courtesy of [LIDARIS](#))*

For UV lasers, absorption is a critical parameter in addition to the existence of the sub-micrometer sized particulates and other tiny defects. These can be precursors to which UV lasers are sensitive, but not necessarily influence the LIDT of longer wavelength lasers. A defect that is created in a single shot irradiation can lead to modifications in the coating that increase its vulnerability to subsequent shots. If the laser has a high fluence level, more defect precursors are either activated or exposed (or both), thus increasing the fatigue-limited probability of failure. Modifications to the coating materials are produced in the accumulation of shots. Deposition process steps, such as intervening etching, have been effective in reducing the defect precursor population [2].

Figure 2 illustrates the initial damage concentrated on defects, and the subsequent modification (melting, vaporization, etc.) of the larger surrounding coating area. The incipient damage probably increased the absorption coefficients in the coatings and led to melting. At the high spike temperatures of high electric field concentrated points, oxide compounds can reduce to metals. They can also sub-oxidize back to a more absorptive state, thus promoting more electrons into the conduction band and allowing more dielectric breakdown, melting or evaporation. The process can cascade.

While work continues to advance and refine international benchmark standards [ISO 11254](#) and [ISO-21254](#), advanced laboratories like LIDARIS, Spica Technologies and Quantel Laser are promoting the use of pico- and nano-second testing profiles in order to provide a meaningful non-destructive testing method for the laser industry. This standardized testing provides confidence that critical components won't fail prematurely and can resist catastrophic breakdown.

### Summary

UV lasers used in industrial, medical, and communication applications are operated in a multi-pulsed mode. Consequently, they require greater resistance to loss of LIDT due to exposure fatigue. We briefly outlined some of the research and current understanding of the life-limiting causes and effects.

In the introduction, we refer to the need to understand the process involved in creating the high-performance films necessary to unleash the full potential of photonics in industry. Materion Advanced Materials is a leading producer of high-purity [thin film deposition materials](#) for durable optical coatings.

### References

1. [“Ultra Violet Coating Technology: Materials and Processes”](#), Coating Materials News V28, Issue 3.
2. Christopher J. Stolz; Justin E. Wolfe; Paul B. Mirkarimi; James A. Folta; John J. Adams; Marlon G. Menor; Nick E. Teslich; Regina Soufli; Carmen S. Menoni; Dinesh Patel, [“Defect Insensitive 100 J/cm<sup>2</sup> Multilayer Mirror Coating Process”](#), Proceedings of SPIE, Volume 8885, 2013.
3. [“Fundamentals of Thin-Film Growth & Influences on Mechanical and Environmental Durability Properties”](#), Coating Materials News V28, Issue 2 .
4. Frank Wagner, Alexandre Beaudier, and Jean-Yves Natoli, “Discussing Defects Related to Nanosecond Fatigue Laser Damage: A Short Review”, Optical Engineering 57(12), 121904, December 2018

### Authors

**Samuel Pellicori, Consultant**  
Pellicori Optical Consulting, Santa Barbara, CA  
Phone: 805.682.1922, Email: [pellopt@cox.net](mailto:pellopt@cox.net)

**David Sanchez, Sr. Materials/Applications Scientist**  
Materion Advanced Materials, Milwaukee, WI  
Email: [David.Sanchez@Materion.com](mailto:David.Sanchez@Materion.com)