HIGH POWER LASER DAMAGE - THESHOLD ELEVATION

Why Some Optics Damage Below their Published Threshold Values

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REASONS FOR LIDT VARIANCE

Values for Laser Induced Damage Thresholds (LIDTs) can vary. They vary batch to batch and coating house to coating house. But more worryingly, damage thresholds can vary from test house to test house. Inflated values present real expense issues to the end user when their optics damage under seemingly safe conditions.

This is our second whitepaper dealing with threshold elevation due to annealing. Annealing a sample during an LIDT test strengthens the optic and results in a raised threshold value. The sample under test has been "improved", but is at odds with the remaining optics from the same coating run which are not annealed and have a lower LIDT value. This error is orders of magnitude greater than any other test parameter error.

FALSE LOGIC

Logic suggests that damage tests should interrogate the sample as thoroughly as possible in order to give the best test. Hence the following inaccuracies have readily gained acceptance: that *firstly, the greater the percentage of clear aperture area we test, the better, and secondly the more laser radiation we give the sample, the better the test.*

Both assumptions couldn't be further from the truth. Both ignore the material under test, and view the optic as inert with a definite, fixed threshold value. However the truth is that optics are changed by heat, and true logical testing rests in understanding the material properties, whether composite or simple glass. Keeping to appropriate conditions of spot size and limiting total radiation are critical factors for accurate testing.

BACKGROUND

Most optics are glasses which is a common name for amorphous material. Glasses are different from crystalline materials in that they have been formed by quenching and their properties depend both on their thermal history and, importantly the heat treatment they receive after formation. We saw in our previous white paper[1] the effect on threshold of making the irradiated sites closer than the ISO recommended distance (false threshold elevations of over 60%). In the effort reported here, we increase the heat given to the sample by giving each site an overdose of shots per site. Glass is changed dramatically by laser light. It is annealed to give a strengthened version of itself. Laser annealing is used in some commercial processes to produce active electro-optic devices.

It is clear there must be strict limits to the heat given a sample in order to prevent "over-testing" which is a very common mistake. In the quest to catch every defect present, the tester strengthens the sample under test, resulting in a false-high threshold. Trying to make the sites touch or overlap shows an absence of awareness that most tests are performed with the more stable gaussian beam, not a flat top (which are never truly flat). The damaging central portion of the Gaussian beam, the peak power, occupies only a tiny area of the entire $1/e^2$ spot size. Hence testing the entire surface is never achieved and would result in a threshold false limit, regardless of the original quality. Even modest reduction in site separation gives large errors as shown in our previous whitepaper[1].

Gaussian beams are the most stable and are normally used in laser damage testing. The 2-D intensity distribution is shown in Fig.1 [2]

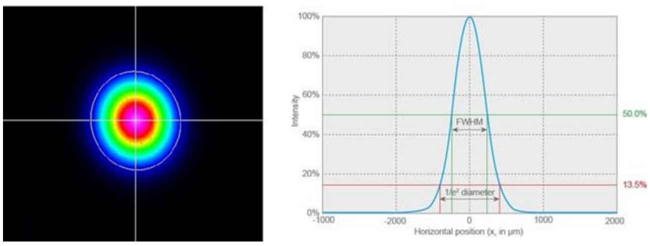

Figure 1

Zero separation enables the tail of intensity beyond the $1/e^2$ spot circumference to overlap with subsequent sites in all adjacent directions. In the nano-second regime this equates to excess heat which is the source of annealing.

LIMITS

BRL's last paper presented both evidence and argument which upheld the ISO standard recommendation of site separation of 2 to 3 times the laser spot size. The present effort gives threshold variation with the number of shots per site used. Annealing the test sample gives rise to errors orders of magnitude more than any other test parameter and thus deserves close inspection.

The most common threshold test is S-on-1, (Several shots on each site). The standard test pattern is shown in Figure 2.

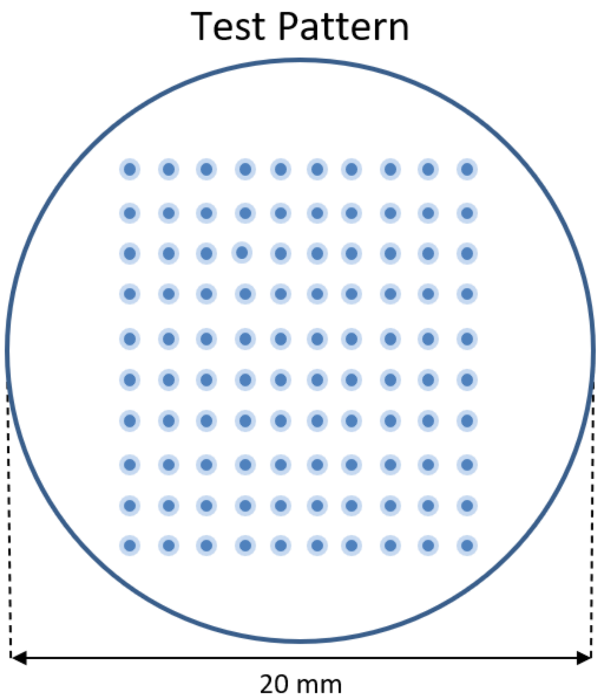

Figure 2

Here each site in a row receives the same power density. Each row varies in power density until a damage pattern is obtained. Multiple sites recognise the need for a statistical response, as the response varies slightly with local morphology. This is why a statistical response is essential for amorphous materials. When a site is tested, the material around the site is annealed hence both site separation and total dosage per site is critical to accuracy. As we give each site more and more shots, the heat around the site increases and the annealed circumference enlarges.

Taking this argument to its conclusion, CW radiation is the best method used in laser annealing. And taking the other extreme a single shot per site (1-on-1) would appear preferential. However the damage event becomes extremely difficult to detect and hence the S-on-1 test has gained preference. There are also some glass materials which require many multiple shots as their insulating properties are high. But the big question is "are all optics amorphous?".

AFFECTED OPTICS

Can this over-testing affect our optics/coatings? The short answer is yes. An important issue with optics is that condensed matter (the coating) is amorphous. Thus the coatings themselves can anneal. The substrate also anneals and crystalline substrates are equally affected as even crystalline substrate surfaces have a high degree of amorphic structure. Both before and after polishing. The most common damage locations are the interfaces:

1. Substrate surface
2. The first coating/substrate interface - this is perhaps the main failure location.
3. Coating/coating interfaces.

If we look at all substrates, both glass and crystal, and all the grey regions of morphology in between these two limits, then we realise that all surfaces contain local regions of varying morphology. Even in single crystal solids, the surface must deviate from its bulk bonding arrangement as it meets the interface boundary of air. And so even the best crystalline substrates require a statistical damage test to gain accurate results.

In Figure 3, we show the difference in electronic states between glass and its equivalent crystal. The work done to gain this data was via electrical conduction research of the bulk, and thus we are mainly looking at a bulk effect. Surface and interface states do show up but would be better represented, for our purposes, if the interrogation was orthogonal to the layers. Laser radiation is orthogonal to the layers, and in AR optics, it passes through not only the bulk, but the coatings, the interfaces and the surfaces on both sides of the optic. It is the interfaces which are generally thought to be the highest energy defect states and thus most easily promoted. Each defect gives an additional discrete localized energy state and thus the damage (bond breaking) occurs in these absorption sites.

Tail states are always present in amorphous structures and they define the glassy state. When the tail states encroach more than is required for a particular wavelength and power rating then exposure to appropriate power levels at that wavelength will cause damage. Defect states can be removed but that art is the hard-won skill set of good coating houses.

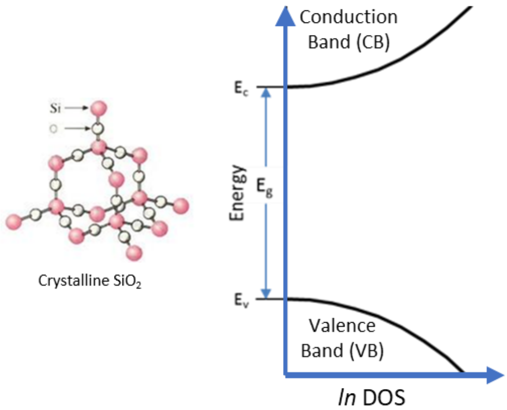

Figure 3a

Figure 3a[3] illustrates a crystalline structure with corresponding electronic states. Figure 3b gives the 2D amorphous equivalent.

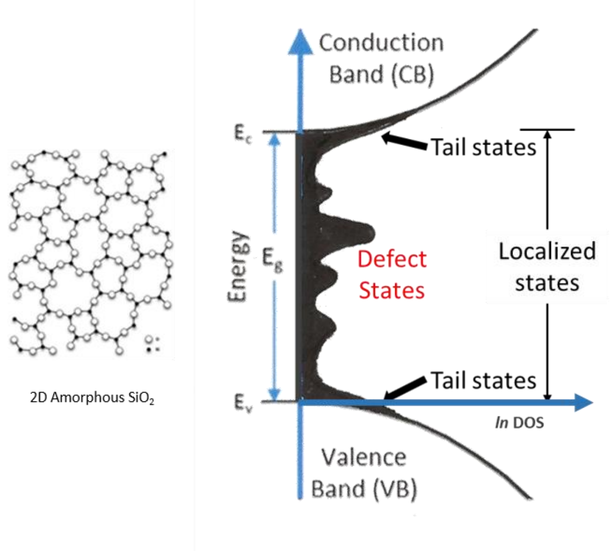

Figure 3b

Cooling glass from the melt is a kinetic time/temp continuum. If cooled very slowly SiO_2 becomes a crystal, all its bond angles and lengths are at their lowest strain spatial positions. If cooled quickly (quenched) to produce a glass, the bond angles and lengths are "frozen in", having no opportunity to anneal i.e. to adjust to a more comfortable (relaxed) morphology. Morphology always dictates band structure. Laser glass rod materials can go through six or seven different annealing cycles to achieve the clarity required.

ANNEALING

Annealing is a process of heating to just below a relaxation point. This allows the material enough energy to undergo small rearrangements and to complete any covalent bonding issues. This technique is used as standard in wafer bonding[4]. Figure 3 above illustrates the density of states (DOS) energy diagram for bulk material. The defects that occur within the coatings and the interfaces (incomplete bonding) also give rise to energy states within the band gap. And as in the case of bulk substrates, coated optics are strengthened by annealing and thresholds are raised. In coated optics both surface and coating interfaces are improved. These processes are extremely expensive. Sapphire substrate surfaces have been improved by reactive ion bombardment[5]. Coated optics can also be annealed to improve the coating-to-substrate bonding and consequently their laser damage threshold (REO)[6].

Laser annealing is known to be more effective on coated optics than other annealing methods e.g. oven or particle bombardment. This become obvious when we note the 3D heat distribution from a point source.

The supremacy of laser annealing was first reported in Proceedings of a Damage Symposium 1987, sponsored by NIST[7]. Structural modification of silica glass by laser scanning has also been reported[8]. CW laser annealing for both substrate surfaces[9] and coated optics is the most efficient. Radiative methods have better and more controllable annealing qualities being able to penetrate through the optic to the coating interface. Oven annealing or even irradiating the full structure, is less controllable and can result in delamination and the substrate bubbling through the coating. This has been frequently observed in heterogeneous wafer bonding, where ultra-thin Si layers perforate and/or delaminate from their SiO_2 substrates during annealing[10].

PARAMETERS AFFECTING ANNEALING

We know the parameters which affect damage testing accuracy are as follows:

1. Inter-site distance
2. Site dosage (number of shots per site).
3. Repetition rate
4. Method of testing i.e. gradually increasing power is the best way to anneal and the worst way to test. It is particularly inaccurate in testing as annealing is a temperature-time continuum. So both thermodynamics and kinetics are salient.

The problem is isolating these various parameters. The time required to do this for each variable is oppressively long and costly. We are a for-profit test house and receive no government funding for these investigations and so time is a premium. Having explored point 1 above, we now examine dosage.

We examined a range of coated samples and, separately, samples from the same coating run with a range of different substrates. The latter sector of samples provides information on the coating/substrate interface which is very different for each substrate material.

EXPERIMENTAL METHOD & CONDITIONS

Each planar AR witness piece was divided into two regions. The first region was tested using 20 shots per site. During this test the other half of the sample was protected against test contamination. The second region was tested using 100 shots per site. The inter-site distance was kept constant at twice the spot size for all tests. The laser parameters were:
Repetition rate= 20 Hz; Pulse duration = 20 ns;
Spot size = 400 microns; Gaussian Fit >95%

We were unsure given the low repetition rate if merely increasing the number of shots per site would induce annealing. It is known if the repetition rate is high, annealing is more easily achieved with CW being the best laser annealing tool. But we kept the parameters the same as for most common tests. We represent the data in term of threshold elevation %.

RESULTS

The effort presented has focused on annealing the sample by using **only a single test variable.** We kept all other variables constant.

Substrate Material	Threshold Elevation (%)
1. Crystalline Silica	40%
2. Infrasil	116%
3. Infrasil	35%
4. NBK7	10%
5. Fused Silica	10%

Table 1

All samples tested increased their threshold when the dosage was raised to 100 shots per site, irrespective of coating type or substrate type. Comparing threshold results obtained using 20 shots per site to those obtained using 100 shots per site proved that increasing the test dosage induces annealing of the sample. Table 1 shows marked increase for particular substrate/coating pairs. One problem we always face is obtaining a range from poor to good optics. Hence we used the same coating run on multiple substrate types, knowing some would be unsuited for that coating. We could only source good quality optics which anneal to a far lesser extent than catalogue optics.

Substrate Material	Threshold Elevation (%)
6. Crystalline Silica	15%
7. Infrasil	53%
8. NBK7	19%
9. Fused Silica	3%*

Table 2

From table 2 we can see *inter alia* that this coating was designed for a fused silica substrate and was an excellent coating as the increase* in threshold was minimal and within normal LIDT error.

CONCLUSION

We have discovered in these preliminary studies that the greatest cause of error in LIDT testing is annealing-induced threshold elevation. Over-testing is the main culprit and is an easy mistake to make via any one of the following:

- Reducing the inter site distance,
- Increasing the dosage,
- Increasing the repetition rate and
- Gradually increasing the power per row.

We have investigated the first two variables and found them conclusive. We know that "good" optics anneal far less than "poor" ones. We also know that complex coatings anneal more than simple (established) coatings. We cannot discuss the particulars of the coating as we don't know them. All we know is whether they are simple or highly complex (multiple) coatings. Coaters are understandably protective of their hard won excellence.

If a sample under test does anneal, then it has been "improved", but is at odds with the remaining optics from the same coating run which are not annealed and have a lower LIDT value. End users, especially laser manufacturers, see the results of this discrepancy.

Thus disobeying the observer effect; allowing the measurement itself to alter the value that it is trying to measure, results in severe consequences.

Damage can lead to systemwide failure. Much of our work is certifying optics for high power laser manufacture. As a company we are regarded as a tough test house. However we refute that and submit this study as evidence of our results being virtually free from annealing effects and a true measure of the coating run capability.

We have tested a common range of substrates and coated optics. Trying to quantify the annealing effect is problematic, but we observed annealing in each and every case.

COMMON ERRORS

We sometimes get requests to test with zero distance between test sites to cover the entire optical surface. Here the end-user wants assurance that there are no defects present which a standard ISO test could miss. We also get requests to use high dosage levels for the same reason. But both of these parameters, if used, would end up with the opposite effect, causing annealing and creating more inaccuracy. Another request is to do a full spot-touching scan with high dosage. As shown in this whitepaper, the results obtained are artificially higher than the true value. Raster scanning does have value but performed at low dosage at a single power density value. It is not suitable for threshold determination.

Hence we recommend an inter site spacing of 2-3 spot sizes. And a minimum dosage, enough to detect damage easily, but low enough to avoid annealing. Annealing is not binary, it is a temperature time continuum and as such is affected by both.

TEST ETHOS

We test representative samples from coating runs. Our test methods ensure we give a power/energy value that enables the end user to be confident of placing that optic into their product without having to anneal it before use.

BRL give more information than just a number. And more than just attention to detail, which we do as a matter of course – as the devil is in the detail. Our forte lies in our range of high level in-house expertise and intelligent testing. We make each test follow appropriate procedures and relay all additional information we have, directly to the customer. In this way we give you a cost effective experience. Our diverse team are highly approachable and interface with coaters and laser physicists alike.

BRL are not unfair to coaters, we are true to the highest test standards. Standards devised and modified over time to give the most accurate results. Optics which BRL have tested have had zero failures in the field.

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[1] Rona E. Belford, Kieran R Ross, "High Power Laser Damage and Annealing", Whitepaper
[2] Figure obtained from Gentec-eo Beam profilers.
[3] Rona E. Belford PhD thesis "Principles and Practice of hybrid sensors. The University of Edinburgh 1986.
[4] Rona E. Belford and Sumant Sood, "Surface activation using remote plasma for silicon to quartz wafer bonding", Microsystem Technologies: Vol. 15(3), 407 2009.
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[6] Dale C. Ness and Alan D. Streater R.E.O. "A laser preconditioning process for improving the laser damage threshold, and the search for subtle laser damage from long-duration laser exposure for IBS thin films", Proc. SPIE 6720, Laser-Induced Damage in Optical Materials: 2007, 67200R (2007)
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