Mitigation of Ultraviolet-Induced Glass Damage in Laser-Sustained Plasma Lamps

Joshua Wittenberg, Michael Navone, Anant Chimmalgi, Quang Giang, Laila Baniahmad, Tim Nguyen, Lauren Wilson, Rahul Yadav
WIN, KLA-Tencor Corp.

Abstract

We have implemented multiple solutions for reducing the risk of lamp burst events inside KLA-Tencor (K-T) Laser Sustained Plasma (LSP) light sources resulting from ultraviolet-induced glass damage. A combination of a judicious choice of operating parameters, a temperature monitoring algorithm, and a new glass material have enabled us to almost completely eliminate lamp-bursts during tool operation, as well as to increase the lifetime of LSP lamps in K-T Broadband Plasma tools, even as they are operated at ever-increasing laser pump powers. These advances have already saved many hundreds of thousands of dollars in raw parts costs from lamp house damage resulting from lamp bursts in current generation Elise tools. They have enabled the operation of the next generation Tesla and Panamera tools at the higher laser pump powers that they require. In addition, our WIN division lamp damage mitigation solutions can be applied to LSP and DC-discharge lamps employed by other K-T divisions, as well as to the reduction of UV-induced damage in glass optics generally.

Introduction

Currently the K-T WIN Broadband Plasma inspection tools use a laser sustained plasma (LSP) lamp house as their light source. Light from a multi-kilowatt diode laser is used to sustain plasma in a conventional Xenon or HgXe Arc Lamp. To satisfy the increasing need for collectible power with each new generation of tool the pump laser power must be increased. As the plasma brightness increases so too does the amount of UV light continuously striking the walls of the lamp. The high flux of light in the vacuum-UV (VUV) region induces bond rearrangements within the glass material that constitute local regions of different stoichiometry of silicon, oxygen, and hydrogen, (Ref. 1). The damage centers generated during this solarization process absorb additional UV light from other components of the plasma spectrum that would otherwise be transmitted by the native glass material, leading to increased temperature within the glass. The higher temperature increases the rate at which damaged glass regions coalesce and a feedback loop develops whereby the temperature and the local concentration of damage centers increase in concert. While mechanisms exist within the glass to "heal" the damage centers via rearrangements that replace the original SiO_2 stoichiometry, eventually the rates of damage center formation and coalescence surpass the rate of healing, and catastrophic damage results, coincident with a rapid temperature increase (Figure 1).

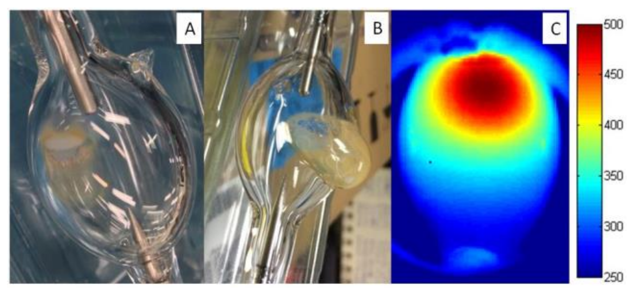

Figure 1: (A) VUV-induced "Mocca" lamp damage (opaque white and brown region). (B) Lamp deformation resulting from extreme temperature following increased UV absorption. (C) Mocca region is 150C hotter than average equatorial temperature.

The primary damage process we have observed is the "mocca effect" (Ref. 1), characterized by a reduction of the SiO_2 species to Si-O and Si-Si bonding moieties, and can be identified by visual inspection well ahead of lamp rupture (Figure 1a). If allowed to progress indefinitely, severe lamp deformation (Figure 1b) and eventual burst (Figure 2) are the result. Each lamp burst requires multiple lamp house optics to be replaced or, in the case of Elise, the entire IR injection assembly. The cost of replacing these optics, combined with the cost of tool downtime, make mitigation of the lamp burst risk an indispensable program component. Additionally, without the ability to reduce lamp damage at current plasma emission levels, future generation tools generating greater radiant flux would not be possible.

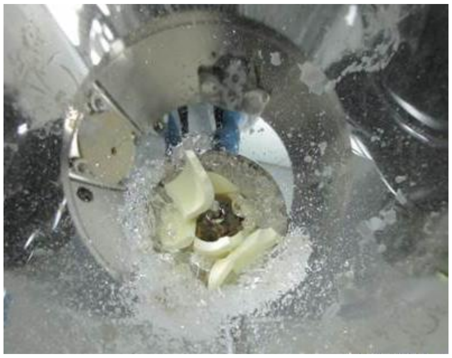

Figure 2: The results of a lamp burst inside a BBP lamp house. Damage to the elliptical reflector requires hardware replacement as well as tool down-time for realignment. The IR injection assembly must be completely replaced as well.

Temperature Control

Considering that the lamp glass damage is the result of the interplay between UV absorption in VUV-induced damage centers, and the increased temperature resulting from that absorption, the initial means of reducing the amount of damage was to reduce the operating temperature of the lamps. Reducing the temperature of the lamp glass, maximal at the internal surface of the glass in the equatorial plane, by ~30C, to below 600C did decrease the frequency of burst events, though the improvement was not sufficient. Lamps still failed within their specified lifetime with a 3-4% probability, causing catastrophic damage to the lamp house optics and long tool-down periods when they did fail. It is reasonable that a reduction in temperature alone was insufficient, considering that the damage center creation is a photochemical process, not a thermally activated one. Considering that the energy required to locally create a damage center is > 7 eV (VUV), then the thermal energy (k_BT) available at either 500C or 600C (66meV and 75meV, respectively) is nowhere near sufficient to influence that process. The effect of temperature is rather to alter the diffusion rates that allow the damage centers to effectively coalesce to larger domains whose greater stability (due to their lower surface to volume ratio) hampers their elimination via any healing mechanism.

Temperature Profile Monitoring

Since decreasing the operating temperature of the lamps was insufficient to prevent their eventual damage within the LSP lamp houses, an algorithm was implemented to monitor the lamp temperature for the rapid change in slope that characterizes lamps exhibiting severe damage (Figure 3). An interlock algorithm based on the absolute temperature of the lamp existed previously, but did not provide evidence far enough in advance of an impending burst. For example, the temperature of the lamp whose data are depicted in Figure 3 never reached the specified interlock temperature of 535C prior to bursting at 520C. An adjustment of the absolute trip point was not a possible solution because, by the end of their lifetime, many lamps approach 535C yet behave normally (this lamp burst before the end of its specified lifetime), and reducing the interlock limit would lead to unnecessary tool downtime for lamp replacements. The new algorithm was designed to calculate the slope of the temperature profile with time, interlocking the lamp house when the value crossed a specified threshold, determined via analysis of temperature profiles of over 100 lamps. The lamp corresponding to figure 3 would have been interlocked and replaced three days before its imminent rupture.

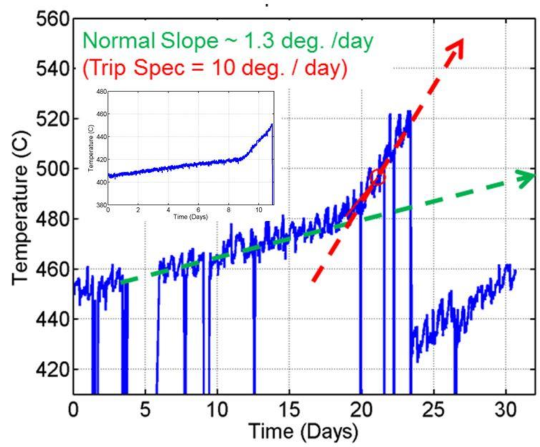

Figure 3: Temperature profile of an LSP lamp. The initial solarization-induced temperature change is normal, but the region of increased slope indicates severe damage. Note the change in slope from 1.3C/day to 10C/day at day 20. The lamp burst on day 23. The temperature profile from day 23 onwards is a new lamp. Inset: This lamp was protected by the algorithm and interlocked prior to bursting.

While such an algorithm did not completely eliminate lamp failures, since 3-4% of these lamps continue to exhibit mocca damage and require replacement, it did eliminate the costs associated with new hardware and optics, and with multiple days of downtime for tool recovery, amounting to multiple hundreds of thousands of dollars per event as well as significant inconvenience to the customer. By contrast, each lamp costs approximately one thousand dollars and requires one hour to replace. The lamp corresponding to the data depicted in Figure 3, inset, was interlocked well before bursting, and was replaced with minimal cost and inconvenience.

Damage-Resistant Glass

The temperature slope algorithm has successfully mitigated the potential catastrophic consequences of lamp glass damage. However, it did not completely eliminate the 3-4% lamp failure rate in current generation tools, and the likely much higher incidence of failures in next-generation LSP sources operating at higher flux. In order to solve these problems, we have developed lamps comprised of glass material exhibiting improved UV damage resistance.

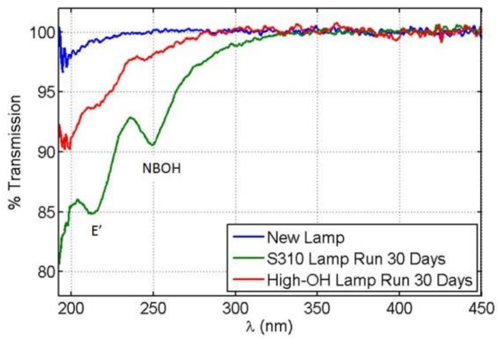

Figure 4: Spectra of Suprasil S-310 glass (Elise) and Spectrosil glass (Tesla, Panamera). Note the reduced E' and NBOH absorption of the newly implemented high-OH Spectrosil glass. The E' and NBOH features are not present in the new lamp, they are induced by VUV damage during operation.

The current generation lamp glass is already a high purity grade, Suprasil S-310, which has an extremely low extrinsic impurity concentration (atoms other than Si, O), and so has very high transmission from visible wavelengths down to 190nm (the shortest-wavelength limit of our next-generation tools currently under development) (Figure 4). Suprasil is a "wet glass," synthetic silica that has been flame-fused in the presence of water vapor to increase the concentration of the Si-OH moiety in the glass material (Ref. 1). The OH loading in the Suprasil S-310 glass is 200-300ppm. Hydrogen atoms are not considered extrinsic impurities, but rather technological impurities, since they are typically added by design. OH loading is known to reduce the intrinsic defects generated by VUV irradiation, via thermally activated reactions that recover the SiO_2 stoichiometry (Ref. 2). The primary defect centers observed that deviate from the native SiO_2 stoichiometry observed are the three-fold coordinated silicon ≡Si• referred to as the E' center, with an absorption peak centered at 215nm, and the non-bridging oxygen hole (NBOH) ≡Si-O• , with an absorption peak centered at 265nm (Figure 4). These are almost non-existent in the as-produced lamps, but they appear as the lamp ages. The increased UV absorption from 190nm-300nm leads to higher lamp operating temperatures as the lamps age, and eventual coalescence of Si-rich regions corresponding to mocca damage (Figure 5). It also means less transmission from 190nm-260nm, which is exactly the wavelength band of the Tesla tool (Figure 4).

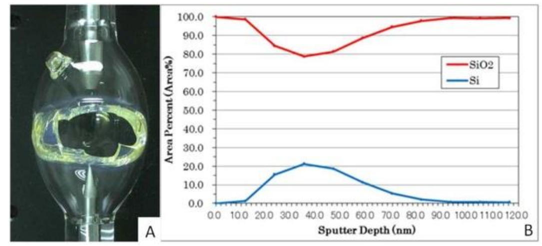

Figure 5: (A) Burst Suprasil lamp (B) Si concentration as a function of depth from the lamp wall inner surface, localized to the "mocca" discolored regions, as measured by X-Ray Photoelectron Spectroscopy.

For the next-generation Tesla and Panamera lamps we have chosen a glass with a higher OH concentration, Spectrosil, and specified an OH loading of at least 1000ppm. We have additionally required that the glass be annealed for at least 40 hours prior to lamp fabrication. Annealing has been shown to remove both Si-H impurities as well as to relax strained bonds, both of which are believed to facilitate the solarization of SiO_2 (Ref. 1, 2). The much more gradual temperature increase of the Spectrosil lamps (Figure 6) during operation is our primary evidence that the lamps are solarizing more slowly, as well as our primary in-situ diagnostic of lamp health. The end result has been lamps that exhibit much less VUV damage (Figure 4), leading to lower temperature operation as the lamps age (Figure 6) as well as lower stress (Figure 7).

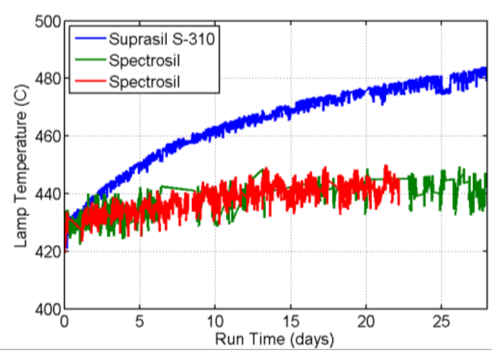

Figure 6: Typical temperature profiles observed during the course of the lamps' lifetime. Note the much more rapid temperature increase of the Suprasil S-310 lamps as compared to two different Spectrosil lamps. This is the result of increased UV absorption. (The difference in the noise levels is the result of different tool configurations, not due to the lamps).

Regardless of the root cause, the increased mechanical stress in the glass is the direct precursor of catastrophic failure. An S-310 lamp run for the same amount of time as a Spectrosil lamp exhibits an increase in stress approximately 75% higher. Note that an unused lamp nevertheless exhibits non-zero stress on account of the 10atm of pressure contained within (Figure 7). The reduced stress in Spectrosil lamps suggests that they could potentially be operated for even longer durations prior to replacement.

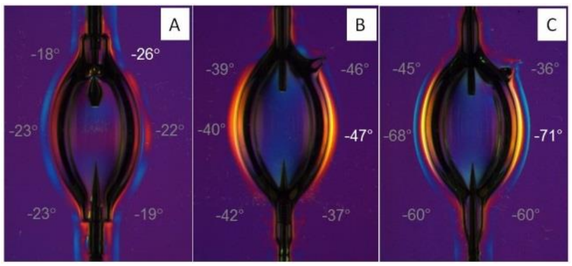

Figure 7: Photoelasticity measurement, to determine change in birefringence resulting from stress in glass material. Larger magnitude (degrees) indicates increased stress. Compared to a new lamp (A), there is increased stress in a used Spectrosil High-OH lamp (B), and still higher stress in a used Suprasil S-310 lamp (C), each run for 30 days.

Conclusions

To date, we have not observed severe glass damage, nor experienced a lamp burst event in any of our final-design High-OH Spectrosil lamps, despite operating them at powers approximately 75% above those experienced by the S-310 glass. Despite the improvements in lamp stability due to the lamp technology improvements, the reduction in operating temperature and the temperature slope monitoring algorithm will continue to be utilized in the operation of the next generation tools, as they provide effective redundant safeguards for the lamp houses without any additional cost. We recommend that other K-T divisions employing LSP or DC-discharge lamps discuss their future use cases and power requirements with the WIN Light Source team in order to take advantage of the knowledge gained during these studies.

Acknowledgements

We gratefully acknowledge numerous discussions, suggestions and technical contributions to this work, by Ilya Bezel, Matt Panzer, the WIN Technology group, and the WIN Engineering light source team.

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Keywords

Laser-Sustained Plasma, Laser-Produced Plasma, Glass Damage, Solarization. DC-Discharge, Lamp