In-situ real-time Langmuir probe and target current investigations of fs-laser irradiated optical components and targets (LPTC)

A stainless-steel chamber having a vacuum system consisting of a turbomolecular pump backed by a dry mechanical pump, where high vacuum of the order of 10^{-7} mbar could be achieved, was designed, built, and tested. The chamber has optical windows for 193 nm, 248 nm and 800 nm laser wavelengths, and a Langmuir Probe (LP) mounted on a vacuum flange that allows for x, y, and z movements, which enables a 3D mapping of the charge ejected during pulsed laser irradiation. The chamber has been tested for ns to fs long laser pulses irradiations of optical thin films. From the analysis of the ejected charge versus laser fluence measurements during pulsed laser irradiation, the Laser Induced Damage Threshold (LIDT) values of various optical materials were estimated.

Simultaneously, the target current (TC) was also recorded during pulsed laser irradiation. When electrons or ions are removed from the optical coating by pulsed laser irradiation, compensating charge is drawn from the chamber by the optical component to maintain its charge neutrality. If the LP intercepts only a small area of the ejected charge cloud, the measured TC accounts for all charges drawn by the optical material. Therefore, the sensitivity of the TC measurement is greatly increased. An image of the LP and TC current traces recorded simultaneously from a HfO_2 film grown by pulsed laser deposition technique on a fused quartz substrate at lower and higher fluences is displayed in Fig. 1. It is evident that the TC currents are larger than those measured by the LP.

Plots of the dependence of total collected and emitted charge on the laser fluence as measured by LP and TC are displayed in Fig. 2. One can immediately observe that there are two regimes. Firstly, there is a region where the measured charge is almost 0 and barely increases with the increase of the laser fluence. When a certain fluence is reached, then there is a sudden increase of the measured charges, which keep strongly increasing with the increase of the laser fluence. This inflexion point in the graph has been identified with the LIDT value measured by LP or TC. A comparison between LIDT values determined ex-situ by optical microscopy and in-situ by LP-TC for HfO_2 and ZrO_2 films deposited in different pressures of O_2 is shown in Fig. 3.

In order to confirm that the values found by the LP-TC method are relevant to the LIDT phenomena in the context of high-power laser infrastructures, the results were compared with the theoretical extrapolation fitting equation defined in ISO 21254- 2:2011(E). The LIDT fluence H_{Th} as a function of the number of pulses (N) for S-on-1 test damage is defined by the standard as:

$$H_{\mathrm{Th}}(N) = H_{\mathrm{Th},\infty(\mathrm{LPTC})} + \frac{H_{\mathrm{Th},1} - H_{\mathrm{Th},\infty(\mathrm{LPTC})})}{(1 + \delta^{-1} \cdot \log_{10}(N))} \qquad (1)$$

The extrapolation curve is related to three fitting parameters namely: $H_{Th,1}$ -the 1-on-1 damage threshold, $H_{Th,\infty}$- the endurance limit of the optical surface and δ a parameter which describes the characteristics damage curve with the number of pulses. The LIDT values determined by LP-TC were integrated in the context of Equation (1) through $H_{Th\infty}$. By setting the endurance limit at the value estimated by LP-TC, it is possible to reconstruct the $H_{Th}(N)$ function for all the investigated samples. The results are presented in Fig. 4 (solid lines). Each curve corresponds to a set of simulated values, which are asymptotically reaching after 10^3 shots the LIDT value determined by LP-TC. When adding the *ex situ* microscopy data to this representation, one can observe that the points fall quite well within the evolution defined by the simulated traces. The result has a profound impact on the understanding and on the advantages of the LP-TC based method for estimating the LIDT value of an optical material. The single pulse measurement of the charges firstly ejected and then compensated in the irradiated film is naturally correlated with the long time irradiation stability of the thin films. Moreover, this coherence between the *ex situ* microscopy and LP-TC approach promotes the methods proposed here as reliable real-time in-operandum control of the optical components. When comparing standard LIDT measurements, 1:1 to 1000:1 with the LPTC and TC measurements, it is observed that the LPTC measurements provide an indication of damage appearance at fluences below the standard LIDT in the single shot. For the 1000:1 case the standard LIDT measurement can exceed the LP-TC value. In contrast, the TC measurements indicate electronic processes taking place at even lower fluences, below 1000:1 standard LIDT. Hence, it is also conjectured here that the TC measurements correspond to the infinity-extrapolated damage threshold. In this way, a conservative LIDT value that predicts the optical component resistance for very long laser exposure can be faster extracted and used for the practical implementation of optical components in high-power laser systems

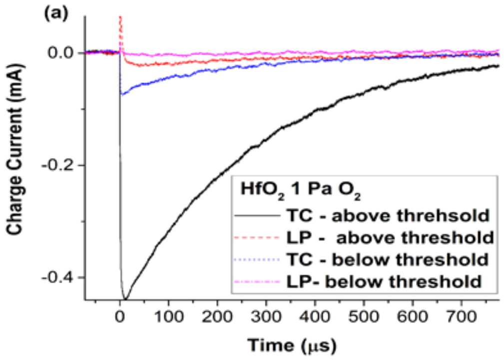

Figure 1. Time-evolution of currents recorded during fs-laser irradiation of HfO_2 thin films at different laser fluences.

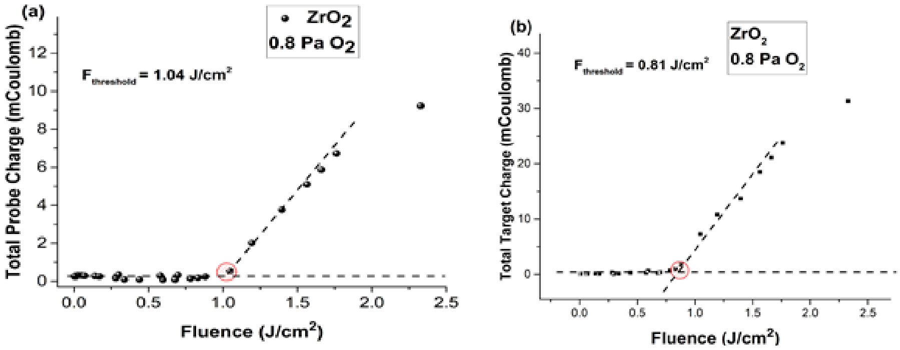

Figure 2. LP total collected charge (a) and target total emitted charge (b) as function of the laser fluence measured for ZrO_2 films.

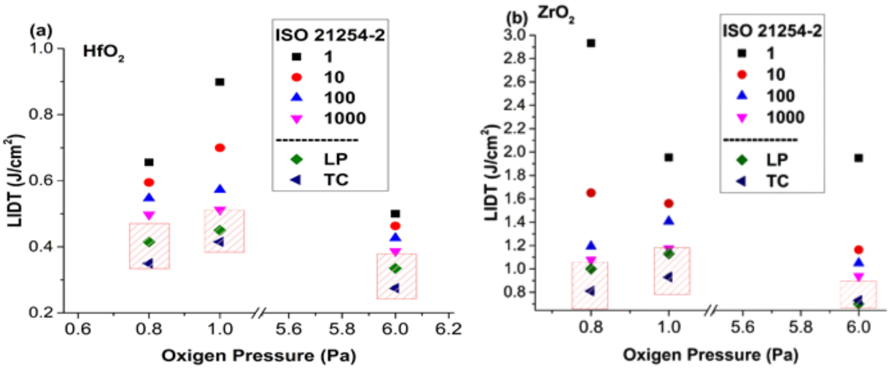

Figure 3. Comparison of the LIDT values determined from ex situ microscopy and in situ LP-TC approach for HfO_2 (a) and ZrO_2 (b) films deposited under different oxygen pressures.

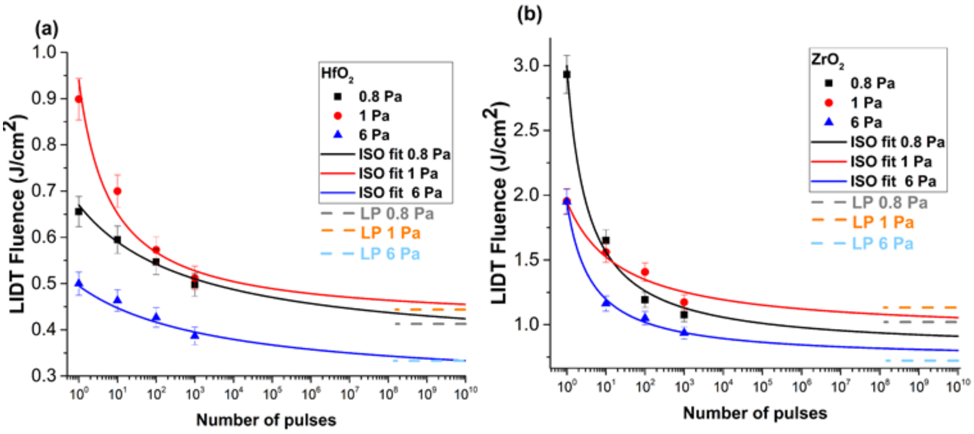

Figure 4. Comparison between the LIDT fluence predicted for a very large number of shots and the value obtained with electrical measurements, for films of HfO_2 (a) and ZrO_2 (b) obtained in different oxygen background pressures. The LIDT values determined by the irradiation of one site with multiple laser pulses are shown with dots. The solid lines are obtained by fitting these values with an analytical function. The dashed horizontal lines indicate the values obtained with electrical methods for a single laser pulse.