Comparing etch rates of poly(methyl methacrylate) ablated by nanosecond and femtosecond pulses of XUV-laser radiation

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Ablation thresholds, etch (ablation) rates, and the quality of ablated structures often differ dramatically with conventional, long-wavelength (100’s of nm) lasers, depending on whether the radiation energy is delivered to the material surface in either short (nanosecond) or ultra-short (femtosecond) pulses [1,2]. Various XUV ($\lambda < 100$ nm) lasers [3-5] with durations ranging from tens of femtoseconds to nanoseconds have recently been placed into routine operation. This has made possible the investigation of how ablation characteristics depend on pulse duration in the XUV spectral region.

The 1.2-ns pulses of 46.9-nm radiation delivered from a capillary-discharge Ne-like Ar laser [6], focused by a spherical Si/Sc multilayer-coated mirror [7] were used for the ablation of organic polymers. Various materials were irradiated [8,9] with ellipsoidal-mirror-focused XUV radiation ($\lambda = 86$ nm, $\tau = 50$-100 fs) generated by the free-electron laser (FEL) operated at the TESLA Test Facility (i.e. the TTF1 FEL [10-12]). Poly(methyl methacrylate) (PMMA) was cleanly ablated with both XUV lasers over a wide range of fluences. Hence, etch rates for two dramatically different pulse durations have been determined. However, the lasers emit at different wavelengths. To account for the wavelength different, the code ABLATOR was used. ABLATOR was developed [13-15] in the early nineties for numerical simulation of ablation of the materials proposed for first walls of inertial confinement fusion (ICF) reactors, induced by broad-band emission (~ keV) from

Figure 1: \textbf{Left} – Fluence dependence of PMMA etch rates calculated and measured for nanosecond pulses of 46.9-nm radiation. \textbf{Right} – PMMA etch rates calculated and measured for nanosecond and femtosecond pulses of 86-nm radiation, respectively.
NOVA-driven hohlraum targets. We have upgraded [16] the code to include degradation of the polymer chains, the relatively short attenuation lengths of XUV radiation, etc., and renamed it XUV-ABLATOR. The modified version of the code has been tested by comparing the calculated etch rates for the nanosecond pulses of 46.9-nm radiation to measured values. Calculated values are in good agreement with those measured (see Fig. 1 - left).

The etch rates were further calculated for nanosecond pulses of 86-nm radiation. By comparing the calculated values for ns-pulses with the measured values for 50-100-fs FEL pulses, the influence of pulse duration on XUV ablation efficiency may be evaluated. In Fig. 1 (right) it is shown that sub-100-fs pulses of 86-nm FEL radiation ablate PMMA at lower rates than predicted by simulation with XUV-ABLATOR for ns-pulses at the same wavelength. Taking into account that the ablation occurs in the low-fluence region, where the rate is controlled by attenuation length (for more details see for example [17]) it follows from the results summarized in Fig. 1 (right) that the attenuation length of FEL radiation must be shorter than that derived from the linear absorption coefficient (reported for example in [18,19] and used as a key input parameter in the XUV-ABLATOR simulation for the nanosecond pulses). This may be explained if one assumes that absorption is enhanced for ultra-intense, ultra-short pulses. In the experiment, the FEL-radiation intensity was $10^4$ times higher than that considered at the same fluence in the XUV-ABLATOR simulation. Enhanced absorption of XUV-FEL radiation has been observed in free rare gas clusters illuminated by the focused radiation delivered from TTF1 FEL [20]. In conclusion, the results reported here suggest enhanced absorption of intense XUV-FEL radiation in the organic polymer.

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References

[16] V. Letal et al.: manuscript in preparation