Interaction of intense EUV femtosecond pulses with solids - damage to EUV optical elements

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Interaction of FLASH pulses with solid surfaces at moderate irradiation intensities (10^{11} – 10^{14} W/cm2) was studied. Particular emphasis was put on materials relevant for XUV/X-ray optical elements (i.e. SiC, Si/C multilayers), with additional “simple” materials being irradiated for comparison and to obtain reference data, i.e., for model calculations.

For this purpose a UHV-system was designed based on the experience acquired during phase I of the TTF-FEL. It incorporates a high precision sample manipulator and MCP-based detectors for the reflected, transmitted and scattered VUV-radiation. The entire UHV-system can be translated along the VUV beam axis, for example, to move the sample surface into the VUV focus. Following experiments were performed at FLASH beam line BL2.

We investigated optical damage of solid surfaces induced by intense, short-pulse VUV irradiation. Each sample was irradiated according to a standardized irradiation sequence: low – medium – high fluence; single- and multi-pulse. FLASH was operated at a wavelength of 32.5 ± 0.5 nm, 21.7 ± 0.3 nm, 13.5 ± 0.2 nm with pulse energies up to 10 μJ, and pulse durations of 25 ± 5 fs. The beam was focused onto the sample using a grazing incidence ellipsoidal mirror to a Gaussian beam diameter of typically ~20 μm. The maximum radiation fluence on the sample was therefore approximately 2.5 J/cm^2.

After the run the induced permanent changes of the surface morphology were characterized by a number of techniques (optical microscopy and interferometry, AFM, micro-Raman, micro-XRD) to obtain information on the physical nature of the damage, and to determine damage/ablation thresholds and ablation (etch) rates.

The optical parameters (reflectivity, absorption length) play the key rule in the damage processes. In the optical range, strong nonlinearities of absorption can lead to complete change of the damage mechanism. (For example in quartz the thermodynamical processes are dominated by electrostatic forces and so called Coulomb explosion due to strong nonlinear absorption). In contrary, in the EUV regime, the optical properties were expected not to change up to intensities even higher than ~10^{14} W/cm^2. Since there were no experimental data proving this prediction, transmission through freestanding thin films (silicon and aluminum, covered by their oxide layers) and reflectivity of bulk samples (silicon and amorphous quartz) were studied at 32.5 nm wavelength. Within the accuracy of the experiment the measurements gave no indications for intensity dependent changes of the optical properties. The optical response of the investigated materials appears to be linear up to the maximum attainable intensities ($\approx 10^{14}$ W/cm^2) and deposited energy densities in excess of 10-100 eV per atom. The fact that the optical properties don’t depend on EUV pulse intensity enables to simplify the model of damage processes.

The damage thresholds were estimated from the Nomarski microscopic pictures, AFM maps and white light interferometer maps using the method described in [1] and especially developed statistical method [2] based on the known pulse-energy distribution of SASE-FELs. They were determined at 32.5 nm wavelength for five different materials which are likely candidates for XFEL optics. Following values were obtained: 65 ± 30 mJ/cm^2 for 46 nm-thick a-C layers deposited on a silicon wafer, 197 ± 100 mJ/cm^2 for B_4C slab, 156 ± 75 mJ/cm^2 for polycrystalline diamond slab (CV-diamond), 87 ± 45 mJ/cm^2 for monocrystal of Si, and 141 ± 70 mJ/cm^2 for SiC bulk. One can compare these values with the melt fluence, calculated by summing the heat required to raise the surface layers to the melt temperature and the latent heat of melting. The expected melt thresholds are approximately equal or below the measured damage thresholds.

For fluences just above the threshold, the material simply re-solidifies once the thermal energy has diffused out. It can lead to a phase transition and eventually expansion of the material above the unirradiated surface. Such a behavior was observed in irradiated samples (Figure 1, left). With increasing fluences, material evaporation will occur. At higher fluence, the material will be thermodynamically unstable, and explosive evaporation caused by homogeneous nucleation of gas phase bubbles within this liquid layer, is a likely mechanism for mass removal (Figure 1, right). We estimated temperature at the end of the pulse before the crater had time to form, at the same depth as where the crater surface will be. It exceeds the critical temperature at which the liquid and gas phases become undistinguishable. Thus, material can leave the sample without encountering any phase discontinuity.

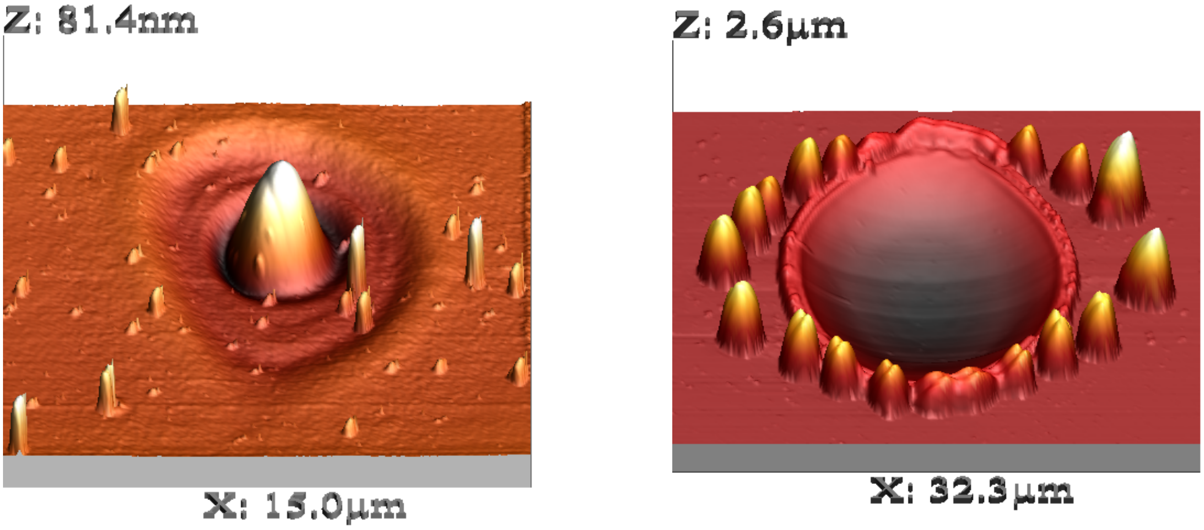

Figure 1: AFM maps of silicon surfaces. Material extrusion after irradiation with FLASH pulses of fluence 325 mJ/c,^{2} is presented on the left picture. On the right – ablation crater surrounded by re-crystallized droplets of melted material blown away from the crater centre after irradiation with pulses of fluence 1100 mJ/cm^2. Pictures have different scale.

This work has been performed within the framework of the *Peak-Brightness-Collaboration* [project II-20022049 EC]. Support from the PBC and the operators of the FLASH facility is gratefully acknowledged.

References

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