Shear wave propagation imaged inside crystalline semiconductors after below melting threshold using Diffraction Near Field X-ray Microscopy

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Material processing with femtosecond lasers has attracted enormous interest over the past decades due to the countless potential applications in technology and industry. One key aspect of their performance is the reduced thermal load, enabling the fabrication of smaller and sharper feature sizes, as well as enabling surface and sub-surface processing of transparent materials. This advantage can be implemented by using laser pulses that are shorter than the time it takes for the strongly excited electron subsystem to transfer its energy to the lattice (typically a few ps). Such pulses can generate highly non-equilibrium states and trigger structural changes within a few hundred fs. The processes involved are almost instantaneous non-thermal melting of a surface layer of several tens of nm, followed by the inward propagation of a sharp melt-front, as well as shock wave propagation into the material.

Time-resolved X-ray diffraction has been successfully used to study non-thermal melting in semiconductors thin films. But, most “real-world” processing applications deal with bulk materials. We have developed a novel technique for imaging ultrafast deformations along the depth in thick crystalline wafers. The technique is based on the ultrafast dynamical diffraction process observable in perfect crystals and the temporal information encode in the Borrmann fan. To this end, we have recently performed a fs laser pump (800nm) - fs X-ray probe (9 keV) experiment at the European XFEL facility. During the experiment, thin Si wafers (300 µm) were investigated as a function of pump laser fluence and delay time. To understand the experimental data we have extended the dynamical diffraction model in to include the ultrafast distortion generated by a laser pulse following the Thomsen model and applied it to the experimental data. This new single shot wavefront sensing reveals the dynamics of laser-induced processes over a wide temporal window along the entire thickness of the crystal wafers.

First results clearly demonstrate the high sensitivity of the technique to small distortions of the lattice cell along the depth of the semiconductor crystal, revealing a shear strain deformation not expected from previous studies performed using conventional pump-probe XRD techniques at fluences below the melting threshold. This new experimental data contradicts previous models of the strain wave propagation, presenting a possible mechanism of coupling between the elastic and plastic deformation at higher fluencies [1].

References

[1] Orthogonal lattice distortions inside crystalline Si upon sub-threshold femtosecond laser-induced excitation A. Rodriguez-Fernandez et al. arXiv:2503.10420