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Imaging of laser-induced microexplosions in dielectrics using time-resolved X-ray diffraction technique

[1] Organization

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[2] Research progress

This joint research project pursues studies of the time dynamics of the formation of novel phases and time evolution of warm dense matter in conditions of ultrahigh pressures and heating/cooling rates (1-10 TPa and 10^{17} K/s) created by a confined micro-explosion inside sapphire single crystal. In order to follow the time evolution of states of matter from hot solid-density plasma to a formation of novel metastable materials, the experiment must utilize synchronized ps laser pump beam and ps hard x-ray probe beam. The ps laser pump with energy of ~100 nJ tightly focused inside Al_2O_3 single crystal transforms sub-micron volume of material to solid plasma which then explodes and generates a powerful shock wave. The subsequent variable time-delayed hard x-ray probe probes time-dependent structural evolution of highly compressed surrounding material. The obtained data would shed a new light on the time evolution of new metastable phases that are formed after laser-generated shock wave inside Al_2O_3 single crystal matrix. A deeper knowledge of the conditions that lead to synthesis of super-dense and super-hard materials, and how this state of matter can be "frozen" during the ultrafast transition to the ambient conditions, can be obtained as a result of these experiments.

[3] Results

(3-1) Research results

The above experiments require deep multi-disciplinary insight into various physical and chemical phenomena, such as intense laser pulse-matter interactions, formation of warm dense matter (WDM) state, X-ray crystallography, and synchrotron beam transient diffraction. The results obtained during previous collaborative studies show that extreme pressures and temperatures can be created with tabletop setup using ultra-short laser pulses tightly focused inside transparent material. Such setup was previously used to create high-pressure bcc-Al phase "frozen" inside sapphire single crystal which was identified by x-ray microdiffraction at the Advanced Photon Source, Argonne National Laboratory (ANL), USA.
The previous X-ray diffraction (XRD) experiments were used to probe the laser-irradiated sapphire under steady-state conditions, i.e., when all transient modifications resulting from the ultrashort laser pulse irradiation became extinct. Here, we aim to extend our previous investigations into the realm of transient modification. For this purpose, a series of time-resolved experiments intended to be carried out at ANL were carefully designed by the participants of this project. In order to promote collaboration on these topics, a mini workshop entitled "Applications of Infrared, Visible, and X-ray Beams for Fabrication and Imaging " was organized on February 1, 2016 at the Research Institute of Electronics, Shizuoka University. The workshop was attended by participating researchers, as well as interested guests and students. Presentations and discussions during the workshop were centered on the following topics:

A. Development of detailed plan for time-resolved XRD experiments

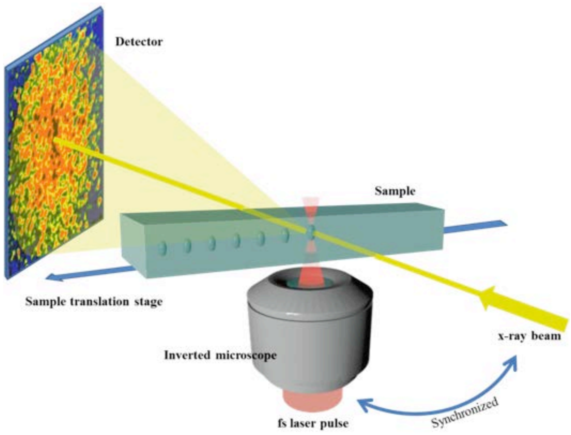

Fig. 1. Time-resolved XRD experiment. X-ray pulse delayed by a variable time with respect to the laser pulse probes transient state of WDM created by the latter. Depending on the delay, different XRD patterns reflecting the transient state can be registered. To ensure that fresh regions of the material are always probed, the sample is translated by a sufficient distance between two subsequent laser shots.

The proposed experiment is shown schematically in Fig. 1. Time-resolved XRD will use thin slabs of sapphire (80-100 μm, thick) in order to ensure high transparency to X-rays. Length of the slab will be large enough to ensure sufficient amount of new undamaged crystal for each new laser shot when the sample is moved between the subsequent laser shots.

The experiments will be performed using a Ti:sapphire amplified laser system and an X-ray probe beam at one of the available beam lines. In order to tightly focus ultra-short laser spot within sub-micron volume of sapphire crystal, a microscope lens will be used. The requirements for the X-ray beam, optical setup, laser and the sample stage are as follows:

- Pump laser: wavelength 800 nm (or 400nm), pulse duration 1.2 ps, energy up to 10 mJ/pulse; optical microscope focusing using high NA optics to create a tight focusing spot inside crystal to ~ 0.4-0.8 μm in diameter (FWHM);
- X-ray probe: polychromatic pink beam; ~ 1 μm focal spot desirable (larger size would be desirable);
- Nano-positioning stage with ~0.1 μm accuracy along xyz axes

The experiment will be carried out as a pump-probe experiment. The x-ray delay time will be varied from 100 fs to 10 ns in accordance to the expected timescale of the transient physical processes in the sample, inferred from the previous experiments, theoretical analysis, and the available literature. It is expected that XRD pattern will depend on the delay between the optical and X-ray pulses.

This setup will allow to study formation and time evolution of WDM created by confined micro-explosion in conditions of extreme pressures and record high heating/cooling rates where the hot solid density plasma forms and transforms into new crystals during several nanoseconds.

It is expected that transient XRD will reveal the following important stages of the laser-induced modification in sapphire:

- Hot, solid density, high-pressure (TPa) plasma, time duration ~ 2 ps, temporal resolution ~10-100 fs. Scattering spectra, aiming for observing density and temperature deviations of the initial stage of micro-explosion;
- Second stage of generation of shock wave and formation of void (~ ns) –scattered X-ray spectra with amorphous and crystalline features; temporal resolution ~10 ps;
- Shock wave propagation and stopping, cooling and crystal stabilization in 10-20 ns. Observation of a new crystal/amorphous stages formation, temporal resolution 100 ps;

B. Steps necessary for practical realization of the proposed experiments

In order to carry out these experiments, access to a relevant beam line at the Advanced Photon Source of ANL is the most important. For this purpose, a General user proposal (GUP) entitled "Time-dependent characterization of Warm Dense Matter created by laser-induced microexplosion" intended for the beam line time application was worked out during the mini-workshop and afterwards. Main idea of this proposal follows the principles described above. Particular details discussed between the participants and included into the plan also involved the necessary preparatory steps, and actions of the participants during the experiments. At the moment of this writing, the GUP has already been submitted for review.

(3-2) Ripple effects and further developments

Exchange of scientific expertise between the participants

was very helpful for coordination of experimental and theoretical work towards the goal of this project. Also, it has contributed to strengthening of domestic and international collaboration at Research Institute of Electronics.
It must be also stressed that joint work of all participants during the mini-workshop and informal discussions have broadened the scope of existing domestic and international research collaborations at RIE, as well as opened new venues for collaboration in the future.

[4] Achievements

List of publications:

(1) M. Malinauskas,A. Zukauskas,Y. Hasegawa,V. Hayasaki,V. Mizeikis, R. Buividas, S. Juodkazis, "Ultrafast laser processing of materials: from science to industry", Light: Science & Applications , accepted (2016).

Travelling report

Name:	Dr. Arturas Vailionis
Affiliation:	Stanford Nano Shared Facilities, Geballe Laboratory for Advanced Materials
Period of time:	2016.01.30-02.02
Destination:	Shizuoka University, Japan
Purpose:	To carry out a joint research, plan the future collaboration, participate at the mini-workshop and report previously obtained results.
Name of receiver:	Prof. Vygantas Mizeikis

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Period of time:	2016.01.31-02.02
Destination:	Shizuoka University, Japan
Purpose:	To carry out a joint research, plan the future collaboration, participate at the mini-workshop and report previously obtained results.
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