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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 research project addresses 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 the proposed experiment, laser pump pulse with energy of ~100 nJ tightly focused inside a single crystal of Al_2O_3 or other potentially interesting material transforms sub-micron volume of material to solid plasma which then explodes and generates a shock wave, which compresses the surrounding material. his process is monitored using variable time-delayed x-ray probe pulse. The obtained data would reveal time evolution of new metastable phases that are formed after laser-generated shock wave, 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. Schematic layout of the experiment is shown in Fig. 1.

[3] Results

Our previous successful collaborative studies have shown that extreme pressures and temperatures can be created with tabletop setup using ultra-short laser pulses tightly focused inside transparent material. Such setup was used to create high-pressure bcc-Al phase "frozen" inside sapphire single crystal, which was identified by x-ray micro-diffraction at the Advanced Photon Source, Argonne National Laboratory (ANL), USA. Time-resolved experiments, in addition to ultrashort laser, would require availability of pulsed X-ray synchrotron source. Interpretation of such experiments would require a deep multi-disciplinary insight into various physical and chemical phenomena, such as intense laser pulse-matter interactions, and formation of warm dense matter (WDM) state.

Thus, previous X-ray diffraction (XRD) experiments have successfully revealed steady-state modification in sapphire crystals.　To extend this success to the steady-state, access to pulsed X-ray source is required.　It is therefore

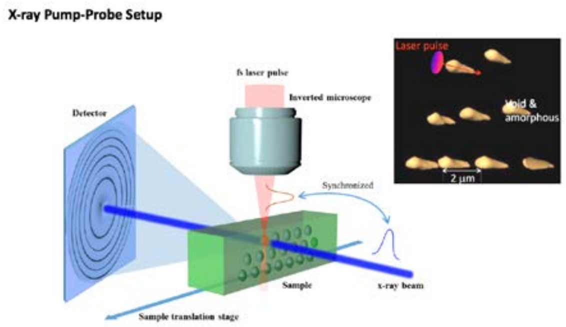

Fig. 1. Time-resolved XRD experiment. X-ray pulse delayed by a variable time with respect to the laser pulse probes transient state of WDM created by the latter. Depending on the delay, different XRD patterns reflecting the transient state can be registered. To ensure that fresh regions of the material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

necessary to get access to a suitable beam line at one of the available pulsed X-ray sources. The main activity of this project is primarily targeting application for a beam time at ANL or SLAC National Accelerator Laboratory (Stanford Ubiversity, USA). Since number of applications greatly exceeds number of available time slots at both facilities, the research plan has to be very convincing to get accepted.

Development of the beam time application was the main purpose of this collaborative research project, and the main topic discussed at the workshop devoted for this project, which was held at Shizuoka University in December of 2016. The workshop was attended by the 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

The proposed experiment is shown schematically in Fig. 1. Time-resolved XRD uses samples shaped like thin slabs of material (slabs of sapphire 80-100 μm, thick were used in our previous steady state experiments) in order to provide samples transparent to X-ray beams. In the time-resolved experiments, crystal is moved to a new position after each pump-probe event to ensure probing of new undamaged crystal for the new pair of pump and probe pulses. The laser system most likely to be used during the experiments is a femtosecond Ti:sapphire amplified laser system. In order to achieve high local optical powers required for crystal modification, tight focusing by a microscope lens will be used. This will ensure focusing spot size diameter of 0.4-0.8 μm.

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 most transparent materials, such as sapphire, silica glass and quartz:

- 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 gain access to a relevant beam line at the Advanced Photon Source of ANL, a General User Proposal (GUP) must be submitted and approved at the facility. Our GUP entitled "Time-dependent characterization of Warm Dense Matter created by laser-induced microexplosion" was submitted several times, but despite significant interest and high marks has not been approved. Therefore, further improvements to be done for new application were one of the main topic of discussions during the Workshop. Participants of the workshop discussed the steps necessary for preparing a successful GUP, and needs to prepare additional portable

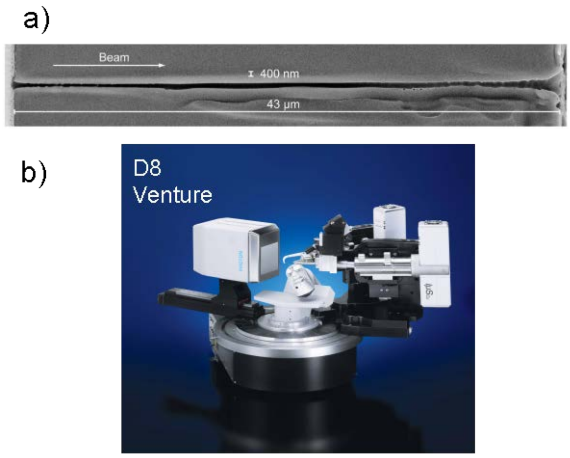

Fig. 2. Cross-sectional view of glass fabricated by Bessel beam illustrates the increased photomodified volume (a), the increased volume can possibly be characterized by the available laboratory X-ray diffraction equipment.

equipment (such as optical microscope) for used during experiments. At the moment of this writing, next version of GUP is under preparation and will be submitted shortly.

In addition, new ideas on how to carry out X-ray characterization were discussed. In particular, Dr. Vailionis has proposed the possibility to use laboratory X-ray sources which are easily available, rather than accelerator-based sources. In order to collect sufficient diffracted signal using laboratory source, one has to increased the volume of material probed by the X-ray beam. Dr. Vailionis pointed out some previous work of Prof. Juodkazis, where large volume of material can be modified simulataneously using non-diffracting Bessel beam. Some examples of the achievable modified region size, and types of laboratory X-ray equipment are illustrated in Fig. 2. Although this possibility applies only to static X-ray characterization, it is highly attractive because the required X-ray diffraction equipment is already available.

(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. 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. Joint work and discussions between the participants of this project 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:

Travelling report

Name:	Dr. Arturas Vailionis
Affiliation:	Stanford Nano Shared Facilities, Geballe Laboratory for Advanced Materials
Period of time:	2016.12.6-9
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

Name:	Prof. Akira Saito
Affiliation:	Division of Precision Sci. & Technology and Applied Physics, Graduate School of Engineering, Osaka University, Japan
Period of time:	2016.12.8-9
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