L.1: Study of shock wave propagation in silicon crystal by picosecond time-resolved X-ray diffraction

The plasma generated during the interaction of a high intensity ultra-short laser pulse with a solid surface, is a source x-rays of high brightness and sub picosecond duration. These pulses provide a unique opportunity to study the structural evolution of a material under external excitation, in real time. Here we report the response of a silicon (111) crystal compressed by a laser induced shock wave, employing time resolved x-ray diffraction technique in symmetric Bragg geometry. The lattice compression is manifested in terms of broadening of the diffraction pattern. Recording of rocking curves at different times provides information on transient strains generated under the shock wave propagation. Further, the use of probing x-ray pulses of different photon energies can directly give information of shock penetration depth. This makes this technique promising for studying the temporal and spatial profile of propagating shock waves.

The experimental study was carried out with the 45 fs, 10 TW Ti:Sapphire laser system. The schematic experimental setup is shown in Fig. L.1.1 (a). A part of the uncompressed (200 ps) pulse was used to irradiate a 500 μm thick flat Si (111) crystal (d = 6.271 Å) at an intensity of 6 GW cm^{-2}. The other part of the uncompressed laser beam was compressed to 45 fs and focussed onto solid (titanium, iron and copper) targets to generate short K_α x-ray probe. The time delay between the pump laser pulse and the probing x-ray pulse was adjusted by setting the pump pulse on an optical delay line. A positive delay here means the pump laser pulse is leading the probe x-ray pulse. The diffracted x-ray spectrum was recorded on to an x-ray CCD camera. The point x-ray source allows a direct imaging of a part of the crystal surface on to the x-ray CCD camera.

This enables simultaneous recording of the diffracted x-ray spectrum from the laser irradiated and pristine area of the crystal. Fig.L.1.1 (b) shows the CCD image of the diffracted titanium K_α (4.5 keV) x-rays from laser irradiated Si (111) surface at a delay of + 600 ps. The lower part of the picture shows the pristine sample where the K_α lines are clearly identified. The upper part of the picture shows blurring of the of the K_α lines because of the non-uniform lattice compression attributed to cumulative effects of the laser induced compression wave and the associated thermal broadening of the lattice.

The measured Si (111) rocking curves at various delay times between -300 and +1800 ps are shown in Fig.L.1.2. The x-ray spectrum shows that the diffraction profiles of Ti $K_{\alpha1}$ (4510.8 eV) and $K_{\alpha2}$ (4504.9 eV) are well resolved for zero and negative delays. It is observed that the diffraction pattern broadens with increasing time delay upto +900 ps. After that, the broadening reduces and finally comes back to original state for delays > +1500 ps. It may be noted that the broadening of the diffracted signals towards higher angles implies lattice compression induced by pump laser beam. On the other hand, the spread towards lower angles reveals the signature of thermal disordering effect.

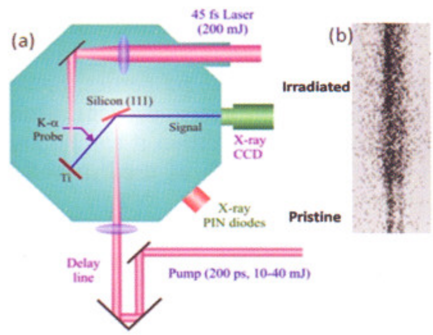

Fig.L.1.1 : (a) Schematic experimental setup (b) CCD image of the diffracted x-rays showing irradiated and pristine parts of the crystal.

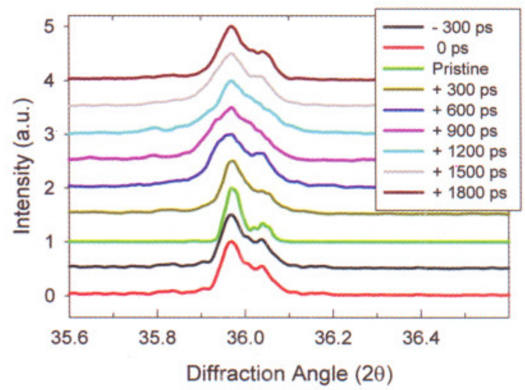

Fig.L.1.2: Evolution of Si (111) rocking curve for various time delays, at an irradiation intensity of 6 GW cm^{-2}.

The time evolution of the rocking curve signifies the propagation of laser induced shock waves inside the crystal. As the shock wave propagates through the crystal, different planes of the crystals are strained differently resulting in the broadening of the rocking curve. At later times, the separation of K_α peaks signifies the passing of shock waves beyond the maximum probe depth inside the crystal. The shock velocity deduced from these measurements is 8.4×10^5 cm/sec, consistent with predicted velocities and probe depth. The observed maximum compression is 0.4 % which corresponds to a pressure of 0.9 GPa.

Reported by:
V. Arora (arora@rrcat.gov.in), S. Bagchi,