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Optical switching of X-rays using laser-induced lattice expansion

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The optical switching of X-rays using laser-induced crystal lattice expansion is described. Irradiation of a gallium arsenide (GaAs) crystal using picosecond laser pulses shifts the Bragg angle through the lattice expansion with a response time of a few hundred picoseconds. A single pulse was extracted from the synchrotron radiation pulse train using a double-crystal arrangement of GaAs, in which the two crystals were irradiated by way of two successive laser pulses with an appropriate time delay.

Keywords: lattice expansion; Bragg reflection; time-resolved X-ray diffraction; picosecond pulsed lasers; SPring-8.

1. Introduction

Recent developments involving intense pulsed X-ray sources using synchrotron radiation and laser-produced plasma are facilitating fast-time-resolved X-ray diffractometry. The combination of femtosecond or picosecond pulsed lasers and time-resolved diffractometry has opened up innovative methods for investigating the dynamics of crystals such as lattice expansion (Chen *et al.*, 1996, 1999*a*,*b*; Larson *et al.*, 1996), shock-wave propagation (Rose-Petruck *et al.*, 1999), phase transition (surface melting) (Chin *et al.*, 1999; Larsson *et al.*, 1998) and acoustic phonon vibration (Lindenberg *et al.*, 2000; Reis *et al.*, 2001; Cavalleri *et al.*, 2000) for both semiconductors and metals.

Irradiation of a crystal surface using a short laser pulse creates photo-excited electrons, which relax rapidly in less than 1 ps to the lattice vibrational mode promoting lattice expansion, $\Delta d/d$. This leads to a deviation, $\Delta\theta$, of the Bragg angle, θ_B, according to the differentiation of Bragg's law, which states that, for a certain fixed X-ray wavelength, $\Delta\theta = -(\Delta d/d)\tan\theta_B$. When the deviation of the Bragg angle exceeds the relevant rocking-curve width, the laser pulse causes X-rays to be reflected (*switching on*) or to cease being reflected (*switching off*). This switching is especially useful when a response time of less than 1 ns is required, and neither mechanical choppers (Lindenau *et al.*, 2000) nor surface-acoustic wave devices (Kikuta *et al.*, 1984; Sauer *et al.*, 1999) are available.

Fast switching of X-ray pulses allows us to utilize the pulsed X-ray sources as pump sources in pump–probe measurements, where the interval between pump pulses should be longer than the decay time of target phenomena. Much shorter response times may allow for an ultrashort pulse to be shaped from a single synchrotron radiation pulse, as proposed, by using the phonon Bragg switch (Bucksbaum & Merlin, 1999).

In order to achieve optical switching of X-rays using lattice expansion, we should investigate the time-dependence of rocking-curve profiles of a laser-irradiated crystal, including the amount and the speed of the Bragg peak shift, and also evaluate the laser power dependence of the lattice expansion and its reproducibility. In this paper we report the time-resolved rocking curves of a laser-irradiated gallium arsenide (GaAs) wafer and its dependence on laser power density. These curves were determined using a pump–probe technique with a picosecond pulsed laser and synchrotron radiation pulses. We also describe the method of optical switching with a double crystal conducted at SPring-8.

2. Experimental

Our experiments were performed at a hard X-ray beamline (BL29XUL) (Tamasaku *et al.*, 2001) of SPring-8, using an in-vacuum undulator as a light source (Kitamura, 1995, 2000). The synchrotron radiation emitted from the undulator was monochromated at 16.54 keV by an Si 111 double-crystal monochromator (Yabashi *et al.*, 1999; Yamazaki *et al.*, 1999). The X-ray beam incident on a crystal through a 300 μm × 300 μm slit had a flux of around 10^{12} photons s^{-1} with a vertical divergence of 10 μrad. A well collimated X-ray beam with a small diameter is preferable for the experiment, since lattice expansion in a small diffracting area can easily be achieved with a lower power laser. The synchrotron radiation pulse train had a pulse width of 40 ps (FWHM) and an interval of 24 ns at the experiment. A 0.6 mm-thick 76 mm-diameter (001) GaAs wafer was mounted on a multiple-axis high-precision diffractometer in the experimental hutch.

Laser pulses were produced by a regeneratively amplified mode-locked Ti:sapphire laser. The output pulses had a repetition rate of 1 kHz, and the timing was synchronized to the synchrotron radiation pulses with a precision of ±2 ps (Tanaka *et al.*, 2000). The time interval between the laser pulse and the target synchrotron radiation pulse was controlled through the timing of the laser trigger, which was manipulated using a delay unit (Hamamatsu C1097-04) and a delay pulse generator (Stanford Research Systems DG535). An output laser with a pulse duration of 2 ps, a wavelength of 800 nm and a pulse energy of 400 μJ was introduced through a quartz lens (focal length 300 mm) onto the samples at an incidence angle of about 90°.

The diffracted X-ray beam from the GaAs wafer was detected using an avalanche photodiode (APD) with a response time of 1 ns (Hamamatsu C5658-W/0). The signals from the APD were recorded through a Boxcar integrator. The gate of the Boxcar integrator was triggered by the frequency-divided signal of an RF master oscillator of the storage ring, in order to pick up the target synchrotron radiation pulses synchronized to the repetition rate of laser irradiation.

3. Results and discussion

Fig. 1 shows the time-resolved rocking curves for the 004 symmetric reflection from laser-irradiated GaAs. This condition provides a good match between the extinction depth of the X-rays and the penetration depth of the laser for pumping (~700 nm). The solid curve represents the rocking curve 500 ps after laser irradiation. The dashed curve represents the rocking curve 70 ps before laser irradiation. The laser power density at the sample surface, P_l, was 17 mJ cm^{-2}. Laser irradiation shifted the Bragg peak by −2.5 arcsec without any observable change in the profile. This implies a lattice expansion of $\Delta d/d = 4 \times 10^{-5}$. The Bragg peak shift induced by the laser pulse was reproducible when the laser power was moderate enough to cause no damage to the GaAs surface in air. By fixing the crystal at an angle indicated by the vertical dashed line in Fig. 1, the laser irradiation would switch on the reflected X-rays with the same speed as the peak shift.

In order to evaluate the switching speed, we measured the time dependence of diffracted X-ray intensity at a certain offset angle with various laser power densities. Fig. 2 shows the time response of the

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peak shift $|\Delta\theta|$, which is derived from the results of the above evaluation. Triangles and circles in Fig. 2 represent $|\Delta\theta|$ for (*a*) P_l = 17 mJ cm^{-2} and (*b*) P_l = 700 mJ cm^{-2}, respectively. At the higher laser power density of (*b*), noticeable damage appeared on the crystal surface, although the rocking curves had been consistent for 1 h. The rising times (10–90%) of the peak shift for (*a*) and (*b*) are found to be about 300 ps and 400 ps, respectively. The amount of the peak shift for (*b*) is about twice as large as that of (*a*). However, the response time of the switching increases by only 30%. Higher laser power is therefore preferable when performing the switching, as long as it remains below the surface damage threshold.

Fig. 3 shows a schematic diagram of the double-crystal configuration for optical switching. Arrangement of the two crystals in (+,−) geometry made the reflectance of X-rays highly sensitive to the crystal angles. The crystal angles were adjusted to have deviations of $\Delta\theta_1$ and $\Delta\theta_2$ from θ_B. The laser beams were guided through a beam splitter and lenses onto the crystals. The power density, P_l, at the crystals was about 70 mJ cm^{-2}, chosen to be just below the surface damage threshold. The timing of laser shots onto the second crystal (C2) was controlled with an optical delay apparatus. The X-rays diffracted by the crystals were observed with a 1 GHz oscilloscope through an APD detector.

First, we demonstrated on/off switching using double-crystal geometry. Fig. 4(*a*) shows the result of switching on the synchrotron radiation pulse train using a laser shot at the first crystal (C1). The crystal, C1, was set at an angle corresponding to the Bragg angle for the expanded crystal lattice by laser irradiation. The second crystal (C2) was placed to satisfy the on-Bragg condition for the X-rays reflected by C1. Here, the offset angles from the Bragg angle are $\Delta\theta_1 = -12$ arcsec and $\Delta\theta_2 = +35$ arcsec. In Fig. 4(*a*), the synchrotron radiation pulse train with an interval of about 24 ns appears after the laser irradiation at $t = 0$ ns. Then, switching off is shown in Fig. 4(*b*). Both GaAs crystals were set to satisfy the Bragg condition without the lattice expansion: $\Delta\theta_1 = \Delta\theta_2 = 0$. A laser pulse onto C1 at $t = 25$ ns reduced the throughput of the synchrotron radiation pulse train drastically.

A combination of these two techniques enables us to pick up a single synchrotron radiation pulse as shown in Fig. 4(*c*). The first crystal (C1), for switching off the X-ray beam, was set at the Bragg angle without the laser irradiation. The second crystal (C2) was adjusted to satisfy the Bragg condition for the expanded lattice, switching on the X-ray beam using a laser shot. Thus, C2 should have a minus offset angle. Here, the offsets for C1 and C2 were tuned to give higher contrast, and were set at $\Delta\theta_1 = +7$ arcsec and $\Delta\theta_2 = -20$ arcsec. The timing of laser shots used to irradiate C1 (C2) was controlled to occur just after (before) the moment the target synchrotron radiation pulse arrived at the crystals. This double-crystal optical switch has a throughput efficiency of about 10^{-4} with a pulse-to-pulse fluctuation of $\sim 30\%$.

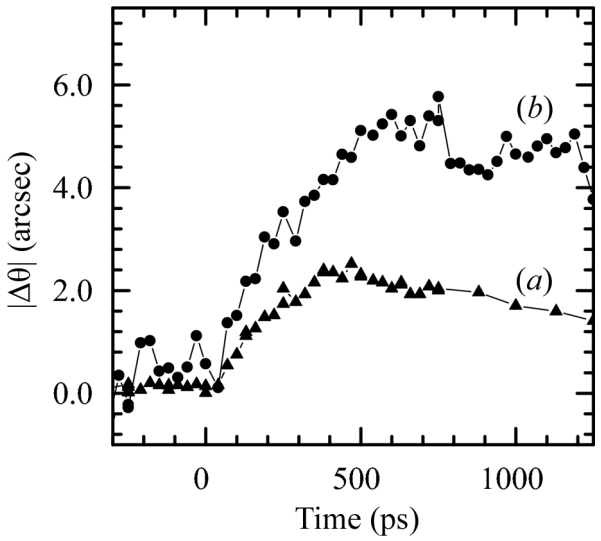

Figure 2
Time response of the Bragg peak shift $|\Delta\theta|$ for (*a*) P_l = 17 mJ cm^{-2} and (*b*) P_l = 700 mJ cm^{-2}. A laser power of 17 mJ cm^{-2} causes no surface damage on a wafer, while the laser power used in (*b*) gives noticeable surface damage. Although surface damage is observed, the lattice response is reproducible for 1 h. The Bragg shift of (*b*) is found to be about twice as large as that of (*a*). The response time (10–90%) of (*b*) is 30% larger than that of (*a*).

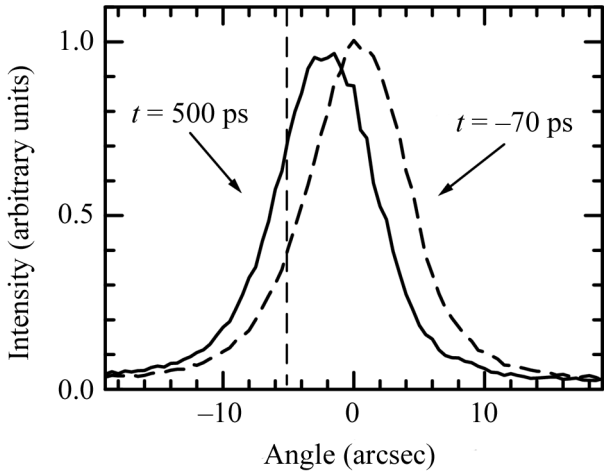

Figure 1
Time-resolved rocking curves for the 004 reflection from laser-irradiated GaAs. The solid and dashed curves represent the rocking curves 500 ps after and 70 ps before laser irradiation, respectively. The laser power density at the surface of the GaAs wafer is 17 mJ cm^{-2}. The Bragg peak is shifted by about −2.5 arcsec without any change in the profile.

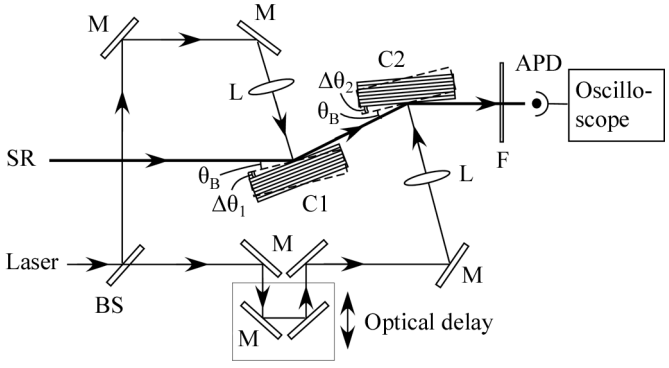

Figure 3
Experimental set-up for optical switching of X-ray synchrotron radiation pulses. Two crystals (C1 and C2) are located in (+,−) geometry. The picosecond laser beams are guided through a beam splitter (BS), mirrors (M) and lenses (L) onto the crystals. The throughput synchrotron radiation (SR) pulses are detected by an APD through an aluminium foil filter (F). With a high-precision diffractometer, the crystal angles are finely adjusted to have deviations of $\Delta\theta_1$ and $\Delta\theta_2$ from the Bragg angle, θ_B. The positions of C1 and C2 which satisfy the Bragg condition without lattice expansion are drawn with dashed lines.

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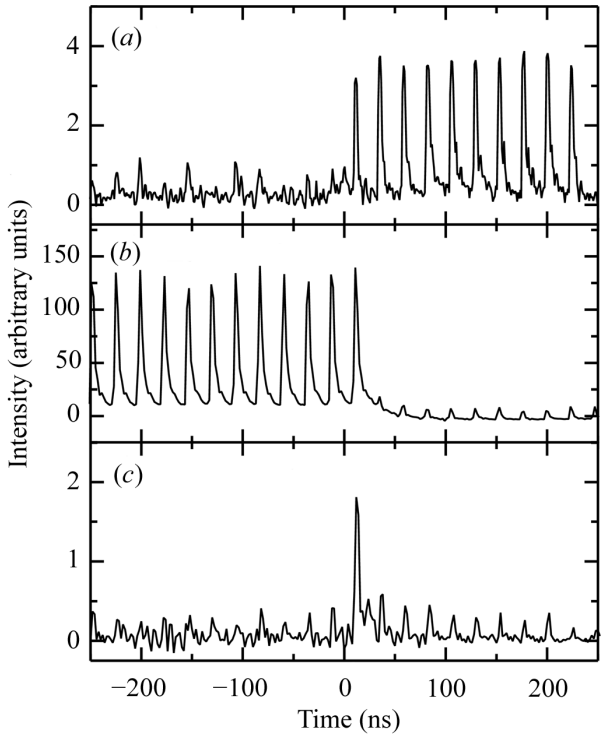

Figure 4
Optical switching for X-ray synchrotron radiation pulses. Laser irradiation of the first crystal determines the on (*a*) or off (*b*) conditions of the switch. A combination of both states of the optical switch selects a single pulse from the synchrotron radiation pulse train (*c*). (*a*) $\Delta\theta_1 = -12$ arcsec, $\Delta\theta_2 = +35$ arcsec. (*b*) $\Delta\theta_1 = \Delta\theta_2 = 0$ arcsec. (*c*) $\Delta\theta_1 = +7$ arcsec, $\Delta\theta_2 = -20$ arcsec.

4. Conclusions

The response time of lattice expansion in a GaAs wafer was measured using a laser pump–SR-probe technique. The rapid change of lattice expansion in a few hundred picoseconds was observed. The amount of the Bragg peak shift and the response time depended on the laser power. At a laser power just below the surface damage threshold, optical switching using lattice expansion was demonstrated to work, using a double GaAs crystal to pick up a single X-ray pulse from the synchrotron radiation pulse train. It should be noted that more rapid changes (with rise times of less than 50 ps) in the reflectivity of X-rays were observed for asymmetric geometry, suggesting the possibility of generating ultrashort X-ray pulses using laser-induced lattice expansion.

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