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Observation of the laser-induced surface dynamics using the single-shot soft x-ray laser probe

軟X線レーザーを用いたフェムト秒レーザーアブレーションの時間分解計測手法の開発

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We have developed a soft x-ray laser (SXRL) interferometer capable of the single-shot imaging of nano-scaled structure dynamics. The depth and lateral resolutions of the interferometer were about 1 nm and 1.8 μm, respectively. By using this interferometer, the initial stage (~50 ps) of the ablation process of the Pt surface pumped by a 70 fs Ti:Sapphire laser pulse was observed. In order to observe the detailed dynamics, the temporal synchronization between the pump and probe pulses was improved to be 3 ps by adopting a portion of the SXRL and pump beams as the time fiducials, to which the pump and probe timing was adjusted by using the x-ray streak camera.

1. Introduction

The dynamical processes of the femto-second laser induced surface modifications such as the sub-micron scaled structures (the ripple and bubble structures) [1], attract much attention for the micro processing by the ultra-short laser pulse. However the details of the femto-second laser ablation process have not been understood. The direct observation of these phenomena is difficult because they are non-repetitive, irreversible and occur very rapidly (pico-second) with a very small (submicron) feature size.

In this study, we propose the pump and probe experiment system using the soft x-ray laser (SXRL) as the probe beam to observe the femto-second laser induced surface dynamics. The SXRL at the wavelength of 13.9 nm is suitable for the observation of the solid surface morphology irradiated by ultra-short pulse laser, because the transmissivity for the high density plasma locating near the solid surface is high and the penetration depth for the solid surface is small (< 10 nm).

2. Pump and probe experiment for observation of the fs laser-induced surface dynamics

In order to obtain single-shot image of the temporal evolution of the nano-scaled structures, a pump and probe soft x-ray interferometer has been developed (see in fig. 1). The spatially coherent SXRL at the wavelength of 13.9 nm [2] is generated from the linearly formed nickel-like silver gain-medium plasmas pumped by the linearly focused CPA Nd:glass laser. The output energy and duration of the SXRL were 0.5 μJ and 7 ps, respectively. Ti:Sapphire laser at the central wavelength of 795 nm with the duration of 70 fs was used as the pump source for the sample. The oscillator of Ti:Sapphire laser was synchronized to that of Nd:glass laser. The interferometer consists of the reflection optics (Mo/Si multi-layer mirrors or Pt mirror). The probe SXRL pulse illuminates the sample with the oblique incidence angle of θ = 24 deg.

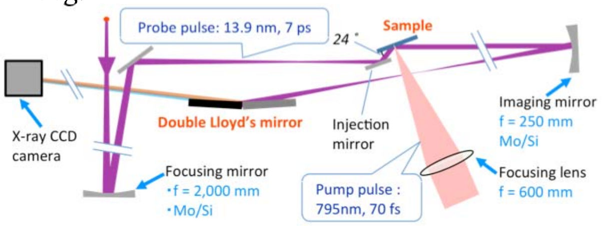

Fig.1. Single shot pump & probe interferometer.

The image of the illuminated area on the sample is transferred to the CCD camera surface by the imaging mirror with the magnification factor of about 20. A double Lloyd's mirror is put between the imaging mirror B and CCD. One of the mirrors covers the reflection from the observation area on the sample, and the other covers that from another area used as the reference, and they are overlapped at the CCD position to make interference pattern. The depth and lateral resolutions were estimated to be 1 nm and 1.8μm, respectively [3]. The temporal resolution is restricted by the duration of SXRL pulse (= 7 ps).

We observed the ablation dynamics of Pt (100 nm thickness) surface by using this system. The typical pump beam energy, fluence and intensity on the sample surface were 130 μJ, 2 J/cm^2 and 3 x 10^{13} W/cm^2, respectively. The focal spot shape was ellipsoidal (see in fig. 2(d)). Figure 2 shows the temporal evolution of the interferogram. The apparent fringe shift to right-ward, implying positive deviation of the sample, was obtained at t = 50 ps. The height at the center of the ablating area was about 34 nm. The left-ward fringe shift, implying negative deviation of the sample, was obtained at $t = \infty$. The origin of surface dilation is supposed as follows; (i) thermal expansion of solid Pt film, (ii) the volume expansion associated with the phase transition from the solid to molten Pt. In the case of (i), thermal expansion will be 2 nm if we assume the thermal expansion of the 100 nm Pt layer associate with the temperature rises from room temperature to the melting point. In the case of (ii), the volume of the melted Pt increases about 8.5 % compared with Pt at room temperature. It corresponds to the expansion by 8 nm in 100 nm Pt film. Thus the surface dilation at the center of the ablating area cannot be explained neither by the case of (i) and (ii). This result implies that the density under the Pt surface decreased by the formation of the nano-bubbles structures. The nano-bubble formations are predicted by Monte Carlo and molecular-dynamics simulations for Si [4]. The time-scale of nano-bubble formations in their report is consistent with our results.

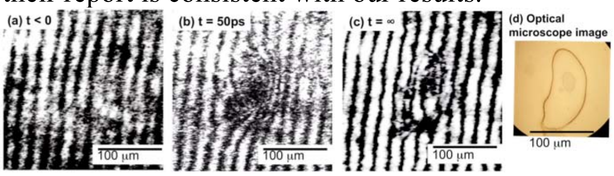

Fig.2. Temporal revolution of the interferogram and optical microscope image of the laser induced Pt surface.

3. Real time monitoring system for the temporal adjustment between the pump and probe pulses

In this experiment, the standard deviation of timing jitter between Ti:Sapphire laser and SXRL was 10 ps, which was measured by the x-ray streak camera (HAMAMATSU 4575-01). In order to improve the precision of the temporal adjustment between the pump and probe pulses, we constructed the real time direct monitoring system by adopting a portion of the Ti:Sapphire laser and SXRL as the time fiducials. The experimental set up is shown in figure 3(a). The SXRL was spatially divided into the probe beam and the fiducial beam (fiducial (X)) at the edge of the mirror 1. The Ti:Sapphire laser was divided into the pump beam and the fiducial beam (fiducial (T)) by the plate beam splitter. The fiducial beams are measured by the x-ray streak camera in every shot (see in fig.3(b)). The influence of the timing jitter between the pump and probe pulse can be removed by this system. The precision of the temporal adjustment between the pump and probe pulses was improved to be better than 3 ps [5].

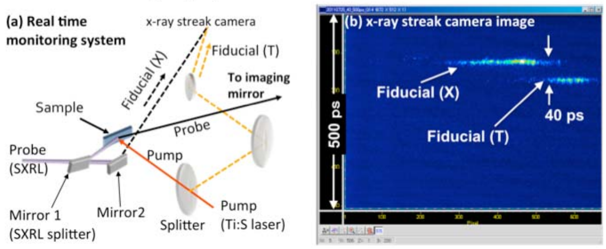

Fig.3. Real time pulse monitoring system for the temporal adjustment between pump and probe pulses.

4. Summary

We have developed a soft x-ray laser interferometer capable of the single-shot imaging of the nano-scaled structure dynamics. The surface dilation speed at the center of the ablating area of the Pt surface was about 700 m/s (34 nm/50 ps), and it implies that the nano-bubble structures were formed in the initial stage of the ablation. In addition, we have improved the temporal synchronization technique between the pump and probe pulses by using the fiducial beams. We are planning to adapt this system to the measurement of the laser ablation dynamics in the next experiment.

References

[1] T. Tomita, *et. al.*: Jpn. J. Appl. Phys. **45**, (2006) pp. L444.

[2] M. Nishikino, *et. al.*: Appl. Opt. Vol. **47** Issue 8, (2008) pp.1129.

[3] T. Suemoto, *et. al.*: Opt. Exp. **18**, (2010) 14114.

[4] P. Lorazo, L. J. Lewis and M. Meunier: Phys.Rev. B. **73**, (2006) 134108-1.

[5] N. Hasegawa, *et. al.*,: *Proc. of SPIE2011 optics and photonics*, in press.