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Si- K_{α} radiation generated by the interaction of femtosecond laser radiation with silicon

A Horn¹, C Kaiser², R Ritschel¹, T Mans¹, P Russbüldt², H D Hoffmann² and R Poprawe^{1,2}

¹ Lehrstuhl für Lasertechnik, Rheinisch-Westfälische Technische Hochschule Aachen, Steinbachstrasse 15, 52074 Aachen, Germany

² Fraunhofer Institut für Lasertechnik, Steinbachstrasse 15, 52074 Aachen, Germany

alexander.horn@ilt.fraunhofer.de

Abstract. Controlling the absorption mechanism, e.g. inverse Bremsstrahlung and resonant absorption, the emission of Si-K_a-radiation using focused femtosecond laser radiation ($t_p = 100$ fs, $\lambda = 850$ nm, I = 20 PW/cm²) has been investigated. The emission Si-K_a-radiation has been improved with double pulses, varying the delay, the energy ratio between pre- and mainpulse and the focal position. The efficiency for double-pulse-generation of Si-K_a-radiation has been increased 4 times compared to single pulse generation.

1. Introduction

Intense laser radiation can generate X-ray radiation. The laser itself does not emit the X-ray radiation, but by hot plasma-matter interaction, where the plasma is generated by the interaction of the laser radiation with matter.

Actually, due to the small emission time in the picosecond range and the micrometer size, using laser-generated X-ray radiation of high brilliance, structural changes can be observed in a pump&probe set-up [1][2]. Especially for diagnostics the K_{α} -emission line is used, enabling high-contrast detection. For example, Si- K_{α} -radiation is used for the detection of aluminum impurities on silicon wafer, because the Si- K_{α} -radiation has a large cross-section for K-shell-ionisation of aluminum.

In this paper, by using double pulses the emission of Si-K_{α} -radiation has been detected by a multilayer spectrograph. The dependence of the emitted Si-K_{α} -photons from the delay and the energy of the double pulses has been investigated.

2. Experimental Set-Up

2.1. Laser and Optics

For the laser generated X-ray radiation a MOPA systems based on an diode-pumped Cr:LiSAF oscillator and a diode-pumped Cr:LiSAF and Cr:LiSGAF regenerative amplifier has been used [3]. The output power of the MOPA system is 100 mW at 1 kHz repetition rate, 100 fs pulse duration and a beam quality $M^2 = 1,3$. In order to reach intensities up to 20 PW/cm² the laser radiation is focused by a chromatic- and chirp-corrected aspheric lens (f = 8 mm) to a beam diameter of about 2 µm. The laser radiation is focused on a silicon wafer with 4" diameter and 20 µm thickness (Figure 1). The lens itself is protected from ablated material by a moving mylar foil in front of the lens. In order to irradiate with

single pulses, a mechanical shutter has been used. Due to the inertness of the shutter a burst of about 10 pulses irradiate the surface. Because of the small Rayleigh length $z_R = 3.5 \,\mu\text{m}$ of the focused laser radiation and the bending of the silicon wafer, the focal position has been compensated by an auto focus system. This auto focus is based on an astigmatic method, which can compensate oscillations of the silicon wafer with amplitudes < 10 μm and oscillation frequencies < 100 Hz. All experiments have been achieved in a vacuum chamber at a pressure $p < 5 \, 10^4$ mbar. The silicon wafer is moved by x-y-axes at a velocity of 20 mm/s with 2 μm precision.



Figure 1. Setup with silicon wafer, photo diodes and auto focus with optics.



Figure 2. Counts of X-ray photons as a function of photon energy for silicon with a moving average red line.

2.2. Delay-Line

Using a delay-line, like a pump&probe set-up, two spatially parallel and temporally separated laser pulses up to 1 nanosecond are focused on the same spot. The two pulses, pre- and main-pulse, have orthogonal polarization and, using prisms and half-wave plates, the energy ratio can be deliberately adjusted. The pulse energy ratio is given by $E_{prepulse}/E_{main-pulse}$.

2.3. Temperature Measurement

The measurement of the hot-electron temperature is achieved by two silicon photo diodes detecting different X-ray energy regimes (Figure 1). The photo diodes are positioned radial to the source and the electrical signals S_1 and S_2 are saved by a digital oscilloscope.

2.4. Spectrography

A multi-layer spectrograph consisting of two multilayer mirrors and a CCD camera (1340x400 pixels) is aligned to detect the X-ray spectra from 1,5 to 1,85 keV with a theoretical spectral resolution of $\lambda/\delta\lambda = 54$ at $\lambda_{_{Si-K\alpha}} = 1,739$ keV. Each multilayer mirror is coated with 100 double-layers consisting of 1.8 nm tungsten and 3 nm silicon and having a maximal reflectivity of about 25% for Si-K_{\alpha}-radiation at an inclination of 4.4°.

3. Results and Discussion

3.1. Si-K_a-Radiation

The generation of X-ray radiation by conversion of visible radiation, e.g. IR laser radiation, needs the mediation by electrons: Due to resonance absorption of laser radiation in the plasma with a critical electron density $n_{crit}^{e}(\mathbf{r},t)$, high-energetic electrons, also called hot electrons, can be generated. The maximal cross-section for Si-K_a-ionisation by electrons is 5,5 keV. An ionized atom with a K-shell hole, generated e.g. by high-energetic free electrons, recombine emitting photons at an energy of some keV. These photons are called K-shell-photons.

The spectrum shows a steadily decaying background of Bremsstrahlung radiation and a characteristic line emission by K_{α} -radiation of silicon at about 1,725 keV (Figure 2). From each

spectrum the relative number of Si- K_{α} -photons has been extracted. Because of the high temperature of the plasma, the K-shell recombination takes place with partially ionized silicon (Si⁺-Si⁸⁺) and the Si- K_{α} -line is broadened to 90 eV [4].

3.1.1. Delay

The relative number of Si- K_{α} -photons changes by varying the delay between pre- and main-pulse and can be increased up to 1.5 times (Figure 3). A relative maximum has been measured at 36 ps, which can be explained by an optimized coupling of the main pulse with the plasma. E.g. the electron density of the plasma surface was at that delay at the critical electron density $n_{crit}^{\epsilon}(\mathbf{r},t)$ (Figure 4).



Figure 3. Relative number of Si-K_{α}-photons as a function of delay (pulse energy ratio 5%).



Figure 4. Position of plasma surface for the critical electron density n_{crit}^{e} for two time steps.

3.1.2. Pulse Energy Ratio

Changing the pulse energy ratio between pre- and main-pulse an optimum can be found at about 35% (Figure 5). The free electrons generated by the ablation of silicon with the pre-pulse interact with the main-pulse resonantly. Because the time where the plasma reaches critical plasma density depends on the pulse energy of the pre-pulse, changing the ratio of the pulse energy means that the delay also has to be varied. A maximal number of photons is reached at 35% pulse energy ratio and about 36 ps delay.



Figure 5. Relative number of Si-K_{α}-photons as a function of pulse energy ratio (delay t = 38 ps).



Figure 6. Relative number of Si- K_{α} -photons and intensity of main-pulse as a function of focal position and delay (pulse energy ratio 36%).

3.1.3. Focal position

The plasma expands and reaches the critical electron density n_{crit}^{e} about 36 ps after irradiation and 35% pulse energy ratio (Figure 6). The generation of Si-K_a-radiation by resonance absorption depends strongly on the inclination angle. By varying the position of the laser focus relative to the surface the inclination angle, here the divergence angle of the focuses laser radiation, is changed (Figure 7).

3.2. Hot-Electron Temperature

 K_{α} -radiation is generated by the interaction of the hot electrons with the inner-bounded electrons of silicon atoms. The kinetic energy of the hot electrons is determined by the cross-section for K-shell ionization by electrons [5]. Assuming a Maxwell velocity distribution of the electrons the spectral energy density $w(E, T_{\nu})$ for Bremsstrahlung radiation is given by

$$w(E,T_h) = \alpha \cdot (T_h)^{-0.5} \cdot \exp\left(-\frac{E}{T_h}\right),$$

where E is the photon energy, α is a generalized plasma parameter, and T_h is the temperature of hotelectrons [6]. When X-ray radiation is generated only by Bremsstrahlung, the measured energy of the X-rays with the photo-diodes w_{pp} is proportional to

$$W_{PD}(T_h) = \int_0^{\infty} T_i(E) w(E, T_h) dE = S_i, \quad i = 1, 2$$

where T(E) is the transmittance of the filter. The ratio of the measured energies S_1 and S_2 for two different filters T_1 and T_2 is independent of α

$$r(T_{h}) = \frac{S_{2}}{S_{1}} = A \cdot \frac{\int_{0}^{\infty} T_{2}(E) \exp(-E/T_{h}) dE}{\int_{0}^{\infty} T_{1}(E) \exp(-E/T_{h}) dE}$$

where A=1.66 is a correction factor for the two photo-diodes. The hot-electron temperature T_h can be calculated by solving numerically the right side of the equation for the measured ratio r. Because of the assumed Maxwell velocity distribution of the electrons, the mean energy of the electrons can be calculated by $\langle E \rangle = 3/2$ T_h and is in a wide range of focal positions constant about 8 keV and increases only at strong defocusing (Figure 8). At maximal relative number of Si-K_{α}-photons the hot-electron- temperature is 7.7 keV being in accordance with literature [7].



Figure 7. Scheme of the focal position 1) focus above 2) on and 3) under the surface.



Figure 8. Relative number of Si- K_{α} -photons and mean electron energy as a function of focal position (delay 36 ps, pulse energy ratio 35%).

4. Summary

Using double pulses and varying the ratio of the energies of pre- and main-pulse and focal position, the number of Si-K_a-photons, compared to single pulse, has been increased. The resonant absorption of laser radiation with the plasma electrons can be improved e.g. by coupling the main-pulse 36 ps after the pre-pulse with a pulse energy ratio of 65%. Also, by changing the focal position of about 8 µm increasing the incident angle the absorption of the laser radiation in the plasma at the critical electron density n_{crit}^{ϵ} can be improved. Compared to single pulses, using double pulses the relative of Si-K_a-photons can be increased about 4 times. These kinds of X-ray sources, having an increased brilliance and ultra-short pulse duration, can be adopted in the future for medical diagnostics, providing a reduced dose for patients.

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