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Determination of irradiation parameters for laser-induced periodic surface structures

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ABSTRACT

The spatial emergence of laser-induced periodic surface structures (LIPSS) on single-crystalline silicon, upon irradiation with linearly polarized picosecond laser pulses (wavelength $\lambda = 1030$ nm, pulse duration $\tau = 6.7$ ps, pulse repetition frequency $f_p = 1$ kHz) was studied theoretically and experimentally, under lateral displacement conditions. An experimental approach is presented for the determination of irradiation parameters of extended surface areas homogenously covered with LIPSS. The approach is based on accumulated fluence and consists of two steps, first the empirical determination of accumulated fluence domain boundaries and second the approximation of irradiation parameters. Such an approach is required for the application of LIPSS in the field of surface functionalization. The approach was successfully applied for structuring extended surface areas, which were homogenously covered with LIPSS. The areas, obtained by different irradiation parameter combinations, satisfying accumulated fluence boundary conditions, show the same type of LIPSS. This observation provides evidence, that the accumulated fluence has a decisive role in the spatial emergence of LIPSS. In the future, further experiments are required to verify the validity and boundaries of the approximations applied.

1. Introduction

The mechanisms leading to the characteristic, periodic and unidirectional formation of laser-induced periodic surface structures (LIPSS, frequently referred to as ripples or nano-structures), have been investigated theoretically [1–4] and experimentally [5–7] since 1965 [8]. Different types of LIPSS have been observed, usually described by their periodicity Λ and their orientation with respect to the polarization of the laser light. LIPSS with a spatial period in the order of the laser wavelength ($\Lambda \approx \lambda$) are usually referred to as low spatial frequency LIPSS (LSFL) and those with significant smaller period ($\Lambda \ll \lambda$) to as high spatial frequency LIPSS (HSFL) [9,7]. It is generally accepted, that for LSFL, Λ is controlled by λ and the angle of incidence θ [10]. The orientation of LSFL is mainly governed by the polarization vector $\vec{E}$ [11]. The origin of HSFL is still under debate and different theories have been proposed [12,9,3].

Recent research is focused on the application of these structures, where broad potential prospects are seen in the field of surface functionalization [13–15]. The application of LIPSS in a flexible and efficient manufacturing process, requires the control of the spatial emergence, of a specific type of LIPSS, on surface areas larger than the focused beam diameter. Mostly, the structures are required to be uniformly distributed on the surface [16].

The spatial emergence is directly related to the intensity distribution of the laser beam in the surface plane. For focused laser pulses with a spatially Gaussian distributed intensity, LIPSS are confined in annular surface regions [7], with excimer laser pulses in more rectangular shapes [17,18] and with a cylinder lens [19] in line like shapes.

LIPSS regions can be extended [20–25] by introducing a lateral displacement of the beam position relative to the surface during irradiation. This displacement has to fulfil certain conditions, when a large area with a uniform structure is to be obtained. To extend structures in one direction, a partial overlap between successive pulses is required, [20]. For irradiation conditions where the displacement applied was too small, an "over-hatch" effect has been observed in literature [16], resulting in the disappearance of LIPSS on the surface.

Usually experiments are carried out to determine irradiation parameters for LIPSS on extended areas. So far, no satisfactory experimental approach has been presented formulating how to determine irradiation parameters for LIPSS areas systematically. Especially theoretical and experimental details about the irradiation under lateral displacement conditions are lacking in literature. In previous work [26] it has been proposed to apply a combination of two D^2-experiments with a specific accumulation function.

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This paper covers the theoretical fundamentals underlying this proposal.

This paper is devided into three parts. A theoretical part, describing the fundamentals and assumptions as well as a derivation of the approximations and simplifications. An experimental part, illustrating the approach by initial verification experiments. A discussion part, justifying the assumptions and classification of the results. The paper is completed with a conclusion part, also containing suggestions for further experiments.

2. Methods

Experiments were carried out with a Yb:YAG laser system (Trumpf, TruMicro 5050), providing pulses with a fixed duration of τ = 6.7 ps, wavelength of λ = 1030 nm, and linear polarization. The system delivers pulse energies E_P up to 125 μJ at a maximum pulse frequency of f_p = 400 kHz. The beam quality, M^2 = 1.15, was determined with a camera based beam diagnostic system (Primes, MicroSpotMonitor).

The energy of the laser beam was attenuated externally, using a combination of a zero order wave plate (Thorlabs, WPH10M-1064) and a polarizing beam splitting cube (Thorlabs, PBS 103/203). The average power $\overline{P}$ was measured with a power meter (Coherent, Field Max II-TO) equipped with a thermophile sensor (Coherent, PM 10).

Beam manipulation, to position the laser beam on the specimen, was accomplished by a Galvanometer-scanner system (Scanlab, IntelliScan 14). The beam was focused perpendicular on the sample surface by a telecentric f-theta lens (Sill Optics, S4 LFT 0080/126) of f = 80 mm focal length. All laser experiments were done in air, at atmospheric pressure and at room temperature.

The inspection of the specimen surface was done by confocal laser scanning microscopy (CLSM, Keyence, VK 9710K). The illumination in the CLSM is accomplished by a laser of 408 nm wavelength. A microscope objective with a magnification of 150× and numerical aperture of 0.95 was used. Morphologies observed were named after their appearance in CLSM.

As a specimen, a flat single crystalline silicon substrate (Melles Griot, PM-1025-Si) was used. The mechanically polished surface has a roughness, determined with CLSM, of about R_a = 12 nm and R_t = 80 nm. Cleaning of the specimen was done before and after laser machining using an Ultra-sonic-bath, filled with Isopropanol for about 10 min.

3. Theory

3.1. Irradiation model

Within this subsection a model is described, which analyses the laser radiation transmitted to the sample plane without considering a laser–material interaction process yet. The input of the model considers parameters of the laser source, optical and kinematical system. The output of the model is the fluence accumulation process in the irradiation plane of the specimen.

For the sake of simplicity the energy deposition is presented here in a Cartesian coordinate system, where a laser beam is assumed to propagate along the positive z direction. The laser is assumed to be pulsed. The fluence ϕ of the laser beam is assumed to show a spatial Gaussian distribution, with ϕ_0 as single pulse peak fluence. Usually a certain number of pulses N_p are released by the laser source at a given frequency f_p, for which the average power $\overline{P}$ can be determined experimentally. The laser beam is focused, under normal incidence, on the surface of the material. The latter is assumed to be parallel to the (x,y) plane. The focused beam radius, usually defined as the $1/e^2$-radius, is denoted here by $\omega(z)$. For the sake of clarity the dependence of the beam radius on the z location is not mentioned explicitly in the following.

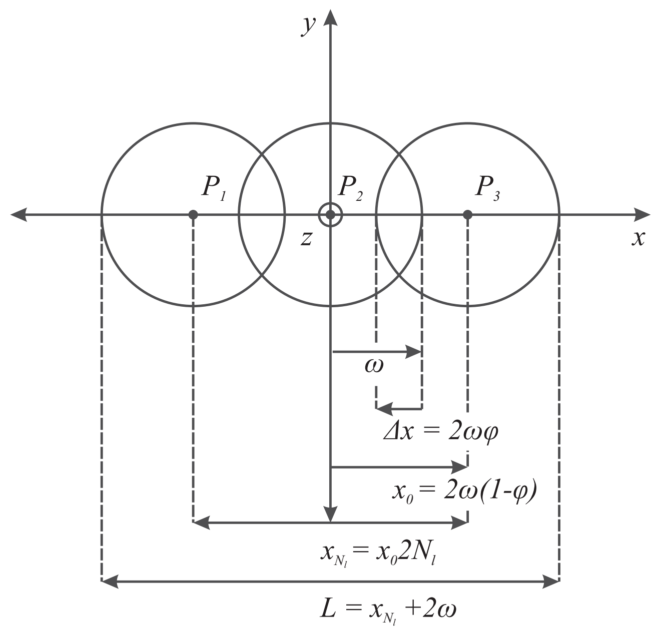

Fig. 1. Schematic drawing illustrating the intersection of displaced laser pulses in x direction. The nomenclature in the y direction is the same as in x direction, but is indicated with index j instead.

The area to be irradiated is assumed to have a flat and squared geometry, with edges parallel to the x and y axis. The edge length L is assumed to be larger than 2ω being the focused beam diameter. These requirements demand beam or sample movements. In order to irradiate each location on the surface, a sequence of linear translations along x and y direction is assumed. The relative velocity is denoted with ν_0. The displacement during the pulse irradiation can be neglected, which implies $\nu_0 \ll 2\omega/\tau$. The velocity is assumed to be equal and constant for both directions. The sequence of irradiated locations is denoted with x_i and y_j. The integers i and j, for the number of displacements, range from $-N_l$ to $+N_l$. The absolute intersection length $(\Delta x,\Delta y)$ of two pulses can be normalized by the beam diameter 2ω, which gives the relative intersection length φ. If φ is given in a percentage, it is usually referred to as overlap [23]. The required boundary for the number of displacements N_l, to cover an area of $L \times L$ with pulses, follows from the definitions illustrated in Fig. 1 and reads

$$N_l = \left(\frac{L}{4\omega(1-\varphi)} - \frac{1}{2(1-\varphi)}\right). \tag{1}$$

The complete sequence of translations is usually repeated N_r times with the same irradiation conditions. N_r is usually referred to as number of over-scans or number of repetitions.

The displacement of laser pulses with Gaussian distributed fluence, results in an accumulated fluence $\Gamma(x, y)$ and in a local fluence $\phi(x, y, i, j)$ on the area, described by

$$\Gamma(x, y) = N_r \sum_i \sum_j \phi(x, y, i, j) \tag{2}$$

and

$$\phi(x, y, i, j) = \phi_0 \exp\left(-2\left(\frac{\left(x + \frac{\nu_0}{f_p} i\right)^2 + \left(y + \frac{\nu_0}{f_p} j\right)^2}{\omega^2}\right)\right) \tag{3}$$