LIPSS WITH EXTREME PROPERTIES: SHORT PERIOD AND HIGH ASPECT RATIO

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ABSTRACT

In this talk parameters and mechanisms of the LIPSS formation with extreme characteristics (period and aspect ratio) on crystalline Si are discussed. We demonstrate transition from 250 nm to 70 nm period upon increasing the incident laser pulse number per site and explain our findings in the frames of the three-step LIPSS formation model, which combines electrodynamic and hydrodynamic processes. We also discuss why further decrease in the LIPSS period does not happen in silicon as the number of laser pulses is further increased. In the second part of the talk the LIPSS with high aspect ratio are demonstrated.

1. INTRODUCTION

The electrodynamic model describes appearance of the LIPSS as a result of interference between the incident laser light and the surface-scattered waves [1, 2]. It predicts that the period of the structure can be controlled primary by the wavelength of the incident laser light as well as by the refractive index of the sample and the environment [3]. The contrast of the interference pattern is not strong enough to cause any selective ablation only in the crests and no ablation in the troughs, hence hydrodynamic processes should be taken into account for correct description of the material redistribution in the melt [4]. The hydrodynamic processes can also induce periodic patterns in different systems lake e.g., phase transitions in solids, waves on liquid surfaces and melt solidification [5]. Here we demonstrate how the combination of the electrodynamic and hadrodynamic models [6] helps explaining the LIPSS periods observed in experiments.

2. LIPSS WITH PERIOD $\Lambda \approx 70\,$nm

LIPSS were formed on a crystalline Si surface exposed to multiple $\tau_p \approx 180\,$fs laser pulses, central wavelength $\lambda = 515\,$nm, The pulse fluence $F = 0.09\,J/cm^2$ was below the single-pulse ablation threshold. The silicon sample was immersed in different liquids during the laser processing, see [7] for more experimental details. The experiments demonstrate that as the scanning velocity decreases (i.e., the pulse overlap or the number of pulses per site increases) the period of the LIPSS jumps from $\Lambda_1 \approx 250 \pm 20\,$nm to $\Lambda_2 \approx 70 \pm 10\,$nm. Interestingly, the same period change was observed in experiments with silicon immersed in liquid precursors for metallic nanoparticles, where the nanoparticles were generated together with the LIPSS [8]. This observation proves that the refractive index of the Si-liquid interface cannot explain the period change observed in the experiments.

Our results can be explained if we treat the LIPSS formation as a sequence of two events: (1) incident light scattering on the surface roughness [1]; (2) development of the ablative Rayleigh-Taylor instability in the melt [4]. The decrease in the period of the structures happens *after* the first LIPSS with $\Lambda_1 \approx 250\,$nm is formed on the surface. At low scanning speed the incident light continues illuminating the surface, on which the large-period LIPSS are formed. Now the following incident laser pulses are scattered by a regular periodic pattern with $\Lambda_1 \approx 250\,$nm, but not by the random surface roughness as it was in the beginning.

The period of the interference pattern formed by overlapping the incident and the scattered waves in this case will be shifted to $\Lambda_2 \approx 70\,\text{nm}$ [9, 7]. The sequence of these events is schematically shown in Fig. 1, in which the laser beam scans the surface from left to right.

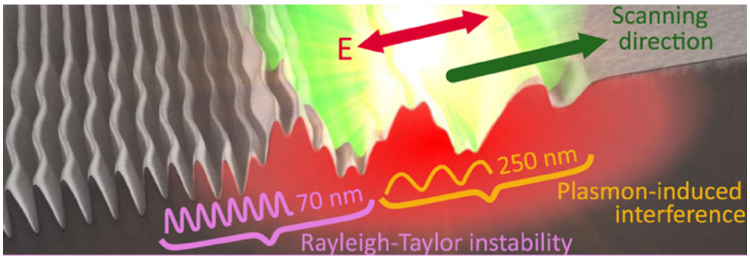

Fig. 1: Formation of LIPSS with $\Lambda \approx 70\,\text{nm}$. Modified from [7].

A further reduction in the scanning speed or multiple surface scanning with the same laser parameters should result in the next LIPSS period reduction: The incident laser pulses should be scattered by the periodic structure with $\Lambda_2 \approx 70\,\text{nm}$ and form LIPSS with $\Lambda_3 \approx 40\,\text{nm}$ [9]. However this does not happen. This predicted period reduction does not occur, since the relocation of the melt on the surface is driven by the Rayleigh-Taylor instability, which fastest growing mode for the given experimental conditions is at $\Lambda \approx 80 - 100\,\text{nm}$, i.e., very close to the observed small LIPSS period of 70 nm. The expected (but not observed) next LIPSS period of $\Lambda_3 \approx 40\,\text{nm}$ is smaller than the critical period of the instability, hence, it cannot grow.

3. LIPSS WITH HIGH ASPECT RATIO

In the second part of the talk, we describe experiments [10], in which the Si surface was first coated with a thin Hf layer of 20 nm, which melting point ($T^m_{Hf} \approx 2500\,\text{K}$) and the boiling point ($T^b_{Hf} \approx 5400\,\text{K}$) are much higher than that of Si ($T^m_{Si} = 1683\,\text{K}$ and $T^b_{Si} = 3533\,\text{K}$). Femtosecond laser pulses at $\lambda = 1026\,\text{nm}$ were used to make LIPSS in ambient environment and under nitrogen atmosphere. The cross section of such LIPSS structure is shown in the scanning electron microscope image in Fig. 2. Remarkably, the depth-to-width ratio of these LIPSS is up to approximately 8:1.

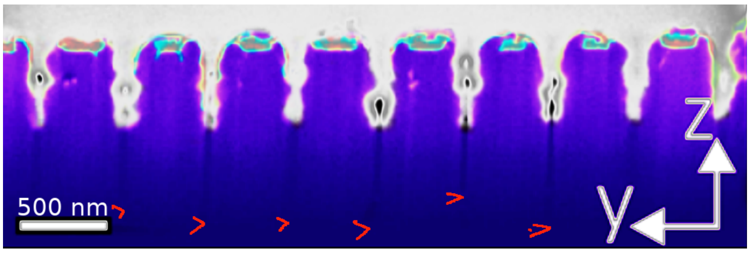

Fig. 2: LIPSS in Si covered with Hf with high aspect ratio. The bottoms of the periodic cracks are marked with red arrows in the picture, while the epoxy glue could not completely penetrate such deep groves. Modified from [10].

The physical processes leading to such a high depth-to-width aspect ratio are not completely clear. Probably, during the laser processing the Si substrate melts below the solid Hf layer at the initial stage of the process. The interference between the incident and the surface waves modulates the surface temperature (of both Hf and Si) periodically, silicon melts, but the material redistribution is suppressed by the solid layer of Hf on the top. Presumably, the temperature and the amplitude of the temperature modulation in Si grows further and may reach the boiling point T^b_{Si} until the Hf overlayer melts and breaks, releasing the overheated Si. After the surface Hf layer breaks, the sample surface looks like a regular set of narrow trenches. The high-aspect ratio LIPSS appear only when the polarisation of the incident light is oriented perpendicular to the orientation of these trenches, suggesting that the incident electromagnetic wave is amplified by the periodic Hf structure.

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