Laser induced tunable Ge2Sb2Te5 phase-change gratings

Pavel I. Trofimov, Irina G. Bessonova, Petr I. Lazarenko, Demid A. Kirilenko, Nikolay A. Bert, Sergey A. Kozyukhin, Ivan S. Sinev

1Department of Physics and Engineering, ITMO University, St. Petersburg, Russia
2National Research University of Electronic Technology, Zelenograd, Moscow, Russia
3Ioffe Institute, St. Petersburg, Russia
4Kurnakov Institute of General and Inorganic Chemistry of the Russian Academy of Sciences, Moscow, Russiapetrofimov@metalab.ifmo.ru

Abstract. Periodic photonic nano- and microstructures are routinely used for light manipulation at the nanoscale. However, their fabrication process is demanding in terms of time, cost and facilities. Here we demonstrate a rapid laser-assisted method for fabrication of gratings in Ge2Sb2Te5 (GST) thin films, based on the formation of laser induced periodic surface structures (LIPSS). LIPSS formation mechanisms dependent on the wavelength of the operating laser, lead to high flexibility of the process, producing gratings with tunable period and orientation with respect to the initial laser polarization. The phase-change properties of GST, on the other hand, allows to fabricate phase gratings with strong modulation of refractive index, which are rewritable in nature.

1. Introduction

Formation of laser induced periodic surface structures (LIPSS) is a well-studied phenomena. The formation of such structures is triggered by the irradiation of the material with ultrashort laser pulses. The incident and scattered light forms the interference picture which is then imprinted in the sample material through the absorption which is usually followed by ablation [1]. However, as ablation implies removal of the material from the surface, such periodic structures are not rewritable in nature.

On the other hand, well known family of chalcogenide phase-change materials (PCM) allows for such flexibility [2]. These materials, for example Ge2Sb2Te5 (GST), possess two different phase states – amorphous and crystalline – which are stable at normal condition and show significantly different physical properties, in particular, the refractive index. Moreover, GST can be reversibly switched between these states at the nanosecond time scale by applying electrical or optical pulses [3]. Therefore the concept of LIPSS formation in PCM is very promising for simple and rapid fabrication of tunable and rewritable periodic photonic structures [4].

2. Result & Discussion

In this work, we demonstrate the laser-assisted fabrication of high-quality phase-change gratings based on the formation of LIPSS in GST thin films. During the process we irradiate 50 and 100 nm GST film on a sapphire substrate with femtosecond laser pulses using a laser system with tunable wavelength (Light Conversion Pharaoh and Orpheus optical parametric amplifier, 1MHz repetition rate, 300 fs pulse duration) to induce a partial crystallization process. We scan the laser beam waist over the 50x50 μm2 areas of the GST film with a piezoscanner to create the phase-change gratings. We then characterize the
quality of the gratings and their periods using atomic force microscopy and study their internal structure with transmission electron microscopy (TEM).

The observed gratings are manifested periodic surface relief in the measured AFM maps, which is formed due to different densities of amorphous and crystalline states of GST. By changing the wavelength of the excitation laser within the range from 800 to 2000 nm, we observed the formation of gratings with periods varied from 110 to 700 nm. AFM image of the structure formed at 1400 nm is shown in Fig. 1a. This type of periodic structures with lines oriented parallel to the direction of laser polarization is usually attributed to the “dielectric” regime of LIPSS formation [5].

In turn, for shorter wavelengths (600–800 nm) we also observed the formation of the gratings perpendicular to the laser polarization which is usually characterized as “metallic” regime [6]. Within a narrow spectral region around 760 nm, we also observed the formation of structures with more complicated geometry that manifested bidirectional phase modulation (Fig. 1b).

![AFM images of the gratings fabricated in 50 nm GST film using different laser wavelengths, which are formed: (a) Parallel to the polarization of the incident light, (b) Perpendicular to the polarization of the incident light. The polarization of the incident light is indicated on the right with an arrow.](image)

To confirm the phase–change nature of GST gratings, we fabricated thin lamellas from our samples and studied the distribution of amorphous and crystalline areas inside the GST films using TEM. TEM images for structures fabricated with femtosecond laser pulses of 1850 and 2000 nm wavelength in 50 and 100 nm thick GST films, respectively, are shown in Fig. 2. The images confirm the modulation of the phase state in the films. Importantly, while we observed nearly full depth crystallization of GST for 50 nm film (Fig. 2a), for the 100 nm film the crystallized areas did not reach the sapphire substrate. Therefore to fabricate homogeneous throughout the entire depth GST gratings at these laser wavelength it is better to use thin GST films with thickness less than 100 nm.
Figure 2. TEM images of the thin lamellas prepared from the phase change gratings. The cuts were made perpendicularly to the grating lines: (a) The cross section of grating created in 50 nm GST film on sapphire with a laser wavelength of 1850 nm; (b) The cross section of grating created in 100 nm GST film on sapphire with a laser wavelength of 2000 nm.

In conclusion, we demonstrated the formation of phase-change gratings in GST thin films. The laser fabricated gratings were formed with tunable period and orientation with respect to laser polarization. The formation of high quality gratings which are rewritable in nature opens up new possibilities for fast, and low-cost fabrication of tunable devices for light manipulation, such as beam steerers and grating couplers.

Acknowledgement
The authors acknowledge the support from Russian Science Foundation (project no. 19-72-10086)

References
[1] Bonse, J.; Graf, S. Maxwell Meets Marangoni — A Review of Theories on Laser-Induced Periodic Surface Structures. Laser & Photonics Reviews 2020, 2000215.
[2] Wuttig, M.; Taubner, T. Phase-change materials for non-volatile photonic applications. Nature Photonics 2017, 11, 465-476.
[3] Au Y.-Y., Bhaskaran H. & Wright C. D. Phase-change devices for simultaneous optical-electrical applications. Scientific Reports 2017, 7, 9688
[4] Kozyukhin, S.; Smayev, M.; Sigaev, V.; Vorobyov, Y.; Zaytseva, Y.; Sherchenkov, A.; Lazarenko, P. Specific Features of Formation of Laser-Induced Periodic Surface Structures on Ge2Sb2Te5 Amorphous Thin Films under Illumination by Femtosecond Laser Pulses. Phys. Status Solidi B 2020, 257, 1900617.
[5] Bonse, J.; Hohm, S.; Kirner, S. V.; Rosenfeld, A.; Kruger, J. Laser-induced periodic surface structures — A scientific evergreen. IEEE Journal of selected topics in quantum electronics 2016, 23.
[6] Fuentes-Edfuf, Y.; Sánchez-Gil, J. A.; Florian, C.; Giannini, V.; Solis, J.; Siegel, J. Surface Plasmon Polaritons on Rough Metal Surfaces: Role in the Formation of Laser-Induced Periodic Surface Structures. ACS Omega 2019, 4, 6939–6946.