Holographic Recording of Surface Relief Gratings on As$_{40}$S$_{60-x}$Se$_x$ Thin Films

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Abstract: The studies of direct holographic recording of the surface relief gratings on amorphous As$_{40}$S$_{60-x}$Se$_x$ thin films are presented. These gratings were created upon exposure to polarized laser beams of various wavelengths ($\lambda = 473 - 650$ nm). The orthogonally $\pm 45^\circ$ linearly polarized light beams were used for recording. The surface structure of the relief gratings was investigated by atomic force microscopy. The influence of laser beam wavelength and spatial frequency of the gratings recorded (grating period $\Lambda$) on the surface relief gratings formation for every composition was examined.

1 INTRODUCTION

Chalcogenide glasses are widely used as materials for fabrication of optics and optoelectronics elements i.e. grids, waveguides, microlenses, photonics crystals etc. (Wang, 2013). During the past 20 years, research in the field of optical materials based on amorphous chalcogenides (ACH) has made significant advances (Kovalskyi, 2006). The photoinduced fabrication of surface relief gratings (SRGs) on As$_2$S$_3$ films has been reported for the first time (Galstyan, 1997). This phenomenon has attracted much attention due to the possibility of direct formation of SRGs (Vlcek, 2009; Gertners, 2010). The photoinduced softening of the matrix, formation of defects with enhanced polarizability, and their lateral drift under the optical field gradient force is believed to be the origin of the mass transport (Saliminia, 2000). The photoinduced formation of SRGs in ACh mainly has been studied in As$_2$S$_3$ films by green light (Teteris, 2013). SRG recording in As-Se system by 650 nm laser was studied by Trunov et al (Trunov, 2010). The composition As$_{40}$S$_{60-x}$Se$_x$ was optimized for recording with 632.8 nm laser light (Reinfelde, 2011).

In this work we present the studies of SRG formation efficiency dependence in amorphous three-component As$_{40}$S$_{60-x}$Se$_x$ films on concentration relationship of S and Se by recording with orthogonally $\pm 45^\circ$ linearly polarized light beams in spectral range of various wavelengths ($\lambda = 473 - 650$ nm).

2 EXPERIMENTAL

The bulk samples of different compositions in systems As$_{40}$S$_{60-x}$Se$_x$ ($x = 0, 10, 20, 30, 40, 50, 60$ at.%) were prepared by direct thermal synthesis from high purity elements (99.999%) in evacuated quartz ampoules. Thin films of glassy alloy were prepared using thermal evaporation technique upon cleaned glass substrates at room temperature (Tesla Corporation, model UP-858 ) at a pressure of $\sim 2 \times 10^{-4}$ Pa, and with evaporation rate 1 - 2 nm.s$^{-1}$. The thickness of thin films was measured directly during their deposition by dynamic weighing method and was about 1000 nm.

The surface relief formation experiments were performed using a holographic recording system (Reinfelde, 2011). All experiments were realized at room temperatures. Recording of SRGs was performed with different lasers $\lambda = 473 - 650$ nm. The orthogonally $\pm 45^\circ$ linearly polarized light beams with equal intensities ($I_1 = I_2 \sim 0.6$ W/cm$^2$) were used for recording, thus providing the optimal conditions for surface relief grating formation. The grating period $\Lambda$ was changed by varying the angle between the recording beams. The readout of the
diffraction efficiency $\eta$ was performed by $p$-polarized light at the Bragg angle using diode lasers (653 nm or 672 nm). The intensity of the first - order diffracted, $I_d$, and transmitted $I_t$, beams were measured using two photodiodes. The kinetics of the recording process was monitored by the time behavior of the gratings diffraction efficiency, determined as $\eta(t) = I_d/(I_t+I_d)$. Such determination of diffraction efficiency characterizes the holographic properties of material taking into consideration the losses associated with absorption, Fresnel reflection and a light-scattering. In all experiments time of the holographic exposure was 9000 sec. The SRG profile height $\Delta h$ was examined by atomic force microscopy (AFM).

3 RESULTS AND DISCUSSION

This part of the work is devoted to the study of the dependence of the first – order diffraction efficiency for each of the compositions in the surface relief formation on the wavelength of the recording laser beams.

Figure 1 shows the dependence of diffraction efficiency of surface relief gratings on the Se-content (x, at.%) in amorphous As$_{40}$S$_{60-x}$Se$_x$ thin films at holographic recording with different wavelength lasers.

First of all, from Figures 1 - 2 we can see that the surface relief formation efficiency changes a lot by changing the wavelength of recording laser beam. All these curves somewhere reaches theirs maximum, i.e. for every wavelength light what is used for the holographic recording exists optimal values of recording conditions for the best performance. This can be explained by the fact that for every composition is optimal wavelength closer to absorption edge of the sample (Sangera, 1996).

As we can see from Figure 2, by changing wavelength laser beam from 473 nm to 561 nm for As$_{40}$S$_{60}$ (x = 0) the best diffractive efficiency is 11,4% at 473 nm, which is different from 561 nm case ($\eta = 0,58\%$).

The maximum value of the diffraction efficiency of 15,2% is achieved by irradiation of the sample As$_{40}$S$_{30}$Se$_{30}$ by wavelength laser beam 561 nm under identical conditions (film thickness $d \approx 1,0 \, \mu$m, exposure dose $E \approx 13,4 \, kJ/cm^2$, x – selenium content, at%).

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The results of detailed studies for grating period influence on diffractive efficiency and SRG formation by 594 nm laser recording are shown in Figures 4 and 5, respectively. The relief depth up to 467 nm was obtained for a period of $\Lambda \approx 3,59 \, \mu$m (see AFM scan in Figure 6). The curves of dependencies show the existence of an optimal grating period $\Lambda_{opt} \approx 4 \, \mu$m, where, at a stated illumination dose E, the profile height $\Delta h$ and diffraction efficiency have a maximum values while falling down versus smaller and greater periods for the same value of E. For
As$_{40}$S$_{60}$ \((x = 0)\) as well as $As_{40}S_{50}Se_{10}$ \((x = 10)\) changes of diffractive efficiency and height profile are not very significant.

At the same time maximum values of the diffraction efficiency $\sim 63\%$ and $66\%$ are achieved for As$_{40}$S$_{30}$Se$_{30}$ and As$_{40}$S$_{20}$Se$_{40}$ thin films, respectively.

According to (Reinfelde, 2014) the grating period affects the SR formation efficiency. The value of $\Lambda_{\text{opt}}$ for holographic recording of SRGs with orthogonally $\pm 45^\circ$ linearly polarized light beams depends on the film thickness and exposure dose. The reason for the existence of $\Lambda_{\text{opt}}$ could be related to some equilibrium state between the surface tension and SR grating formation forces created by the light intensity gradient perpendicular to the film plane.

It is known that the first-order diffraction efficiency for sinusoidal surface relief transmission gratings depends on a relief height is given by $\eta \sim \Delta h/\Lambda$ (Yokomori, 1984). Therefore some similarity in the curves of diffraction efficiency in Figure 4 and curves of relief height in Figure 5 can be observed.

According to (Tanaka, 2011) the optical absorption coefficient at such light quantum energy for chalcogenide materials is about $\alpha \approx 10^4$ cm$^{-1}$. The light penetration depth in the film at such optical absorption coefficient is $d_p = 1/\alpha \approx 1 \mu$m. This value coincides to the thickness of studied films. It is known that the whole illuminated depth of the film, where the laser
light intensity is sufficiently strong, takes part in the formation process of photoinduced SRGs (Reinfelde, 2013).

Consequently, the optical properties of recording material and thickness of the films must be considered for optimization of SRG recording.

4 CONCLUSIONS

The optimal wavelengths for holographic recording of surface relief gratings with orthogonally ±45° linearly polarized light beams in As40S60-xSex (x = 0, 10, 20 ... 60 at.%) thin films have been established. An influence of grating period on surface relief formation efficiency is shown.

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REFERENCES
