Investigation of optical and structural properties of ZnS\textsubscript{0.5}Se\textsubscript{0.5} films

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Abstract. The work relates to the field of physical optics and concerns the study of structural and optical properties of thin films formed from solid solution of ZnS\textsubscript{0.5}Se\textsubscript{0.5} and used to produce multilayer interference coatings operating in the near and middle IR spectral regions. It describes the results of manufacturing optical interference filters using the films of the examined film-forming material.

1. Introduction
The problem is that a limited set of materials suitable for obtaining thin-film optical coatings significantly constrains their functional parameters and characteristics at the design stage, during manufacture and subsequent operation. Therefore, the development of new film-forming materials, as well as work on the improvement of the production technology and methods for the investigation of thin film-based optical coatings are essential tasks in the field of thin-layer optics. To a greater extent, this applies to coatings for the near and middle IR spectral regions and is prompted by the intensive development of thermal imaging equipment, multi- and hyperspectral optical systems for various applications.

Currently, there are tasks related to the development of complex multilayer interference coatings for operation in the spectral range up to 15 μm and more [1–3]. Films of germanium [4] and lead telluride [1, 2, 5] can be used as film-forming materials with a high refractive index in this spectral range while films of zinc sulfide and zinc selenide [1] can be used as film-forming materials with a low refractive index.

The properties of thin optical films of zinc sulfide and zinc selenide have been well studied [6, 7]. The absence of absorption lines in a wide operating range allows to use the films prepared from these substances for the production of optical coatings for the spectral region 0.6 μm to 25 μm. Paired with a material having a high refractive index, such as germanium or lead telluride, it is necessary to use a material having the lowest possible refractive index and compatible with Ge and PbTe films. Among zinc chalcogenides, only ZnS films satisfy this requirement. However, the insufficient repeatability of the properties [6] and the strong temperature dependence of the accommodation coefficient for zinc sulfide films [8] make them of little use for the manufacture of multilayer thin-film precision optical coatings.

It is known [9] that zinc sulfide and zinc selenide form a continuous series of solid solutions. This suggests that, depending on the composition of the solid solution, it is possible to obtain films with a
continuous refractive index value ranging from $n_{\lambda=5\,\mu m} = 2.05$ (for ZnS films) to $n_{\lambda=5\,\mu m} = 2.45$ (for ZnSe films).

We studied the properties of a new film-forming material – ZnS$_{0.5}$Se$_{0.5}$ solid solution – in order to produce on its basis multilayer interference coatings for the near and middle IR spectral regions.

2. Experimental setup and results
Films of ZnS$_{0.5}$Se$_{0.5}$ with a thickness of ~2 μm were deposited on substrates of borosilicate glass, single-crystal germanium and silicon by vacuum evaporation in a VU-2M chamber. The pressure in the chamber was not lower than 5·10$^{-5}$ torr and the temperature of the substrates during deposition was 120°C. Film deposition rate was ~ 8 Å/s. The starting material was in the form of pressed pellets and evaporated from a directly-heated molybdenum foil boat. Film thickness during the deposition process was monitored by the broadband monitoring system IRIS 1017 operated in the reflection mode in the spectral range 950–2500 nm.

The structure and phase composition of the starting film-forming material and of the obtained films was determined by X-ray diffraction analysis using a diffractometer «Dron-2.0» (Cu-Kα). X-ray diffraction analyses were carried out on samples of the starting film-forming material, as well as on samples of films formed on single-crystal germanium and silicate glass substrates. The results of the investigation displayed that the starting material was a solid solution of ZnS$_{0.5}$Se$_{0.5}$ with a cubic lattice based on cubic ZnSe. The lattice constant is $a = 5.56$ Å. It amounts to ≈ 90%, and 10% is also a cubic solid solution but with a slightly larger lattice parameter. The structural properties of the film formed on a germanium substrate are identical to those of the film on the silicate glass. The films are polycrystalline and textured along the plane (111).

Dispersions of the optical constants in the spectral region from 2 μm to 25 μm were determined by a special method [10, 11] from the reflection and transmission spectra with allowance for absorption. The reflection and transmission spectra of films on silicon and germanium substrates were measured on an infrared Fourier spectrometer FSM 1201. Figure 1 shows the calculated dispersion of the optical constants for the ZnS$_{0.5}$Se$_{0.5}$ film in comparison with those for the ZnS and ZnSe films that we studied earlier [2].

![Figure 1](image_url)

**Figure 1.** Dispersions of the refractive index (a) and the extinction coefficient (b) for the films: 1 – ZnS, 2 – ZnSe, 3 – ZnS$_{0.5}$Se$_{0.5}$.

The examined films were used to design and manufacture interference optical filters: a bandpass filter with transmission in the range from 8 μm to 12 μm and a narrow bandpass filter with $\lambda_{\text{max}} = 10.56$ μm and a half-width $\Delta\lambda_{0.5T_{\text{max}}} = 140$ nm. Such bandpass filters are applied in thermal imaging devices operating in the atmospheric transparency window of 8–12 μm. Narrow bandpass filters are used in NDIR-sensors for gas analyzers. For instance, a filter with $\lambda_{\text{max}} = 10.56$ μm is used in gas analyzers for the detection of sulphur hexafluoride (SF$_6$).
Figure 2 shows the spectral transmission characteristics of manufactured IR filters on germanium substrates.

![Figure 2](image)

**Figure 2.** Spectral transmission characteristics of bandpass filter 8-12 μm (1) and narrow bandpass filter $\lambda_{\text{max}} = 10.56 \mu\text{m}$ (2).

3. Conclusions
We have studied the structural and optical properties of films prepared from a new film-forming material – solid solution of ZnS$_{0.5}$Se$_{0.5}$. Dispersions of the optical constants for the examined films were calculated in the spectral range 2 μm to 25 μm. It is found that the value of the refractive index of the examined films is between the values of the refractive indices for the ZnS and ZnSe films. The paper provides examples of a practical use of multilayer IR interference coatings based on the examined films.

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