DIELECTRIC AND TRANSPORT PROPERTIES OF $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ IN ALTERNATING ELECTRIC FIELDS

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The nature of dielectric losses (conductivity losses) and the hopping mechanism of charge carrier transfer in the $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ solid solutions (x = 0.1, 0.2, 0.4) in alternate electric fields ($f = 5 \times 10^4$–3.5×10^7 Hz) were established. The parameters of localized states in the forbidden band of the samples were determined. It was found that the values of the real and imaginary parts of complex dielectric permittivity, dielectric losses tangent and conductivity of studied samples increased with increasing molar fraction (x) of $TlGaSe_2$.

Keywords: transport properties, $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ solid solutions, alternating electric fields, frequency, complex permittivity, dielectric losses, charge transfer, localized states.
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Semiconductor ternary compounds $TlInS_2$ and $TlGaSe_2$ have a layered structure, a small difference in lattice periods and are characterized by strong anisotropy of physical properties, high photosensitivity and optical transparency. Therefore, these materials are promising for applications in photodetectors, photoconverters, pulsed laser radiation detectors and X-ray recording devices.

The physical and physicochemical properties of $TlInS_2$ and $TlGaSe_2$ crystals have been the subject of a number of studies. In particular, the results of low-temperature X-ray studies of $TlInS_2$, $TlGaS_2$ and $TlGaSe_2$ single crystals show that phase transitions occur in them. At room temperature they belong to the layered structural type β-$TlInS_2$ [1]. The dielectric properties and alternating current conductivity of $TlInS_2$ and $TlGaSe_2$ single crystals, as well as the effect of γ-irradiation on them, were studied in [2-4].

The aim of this work is to study the dielectric properties of single crystals of solid solutions $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ (x = 0.1, 0.2, 0.4 mole fractions) and to establish the mechanism of current flow in alternating electric fields in the radio frequency range.

Single-crystal samples of $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ for electrical measurements were made in the form of flat capacitors. Silver paste was used as electrodes for the samples. The dielectric properties of the samples were measured in the direction perpendicular to the layers of single-crystal $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$.The thickness of the studied samples was 650–800 μm, and the area of the plates was 6.5×10^{-2}-10^{-1} cm^2. Dielectric measurements of the samples were carried out using the resonance method at room temperature.

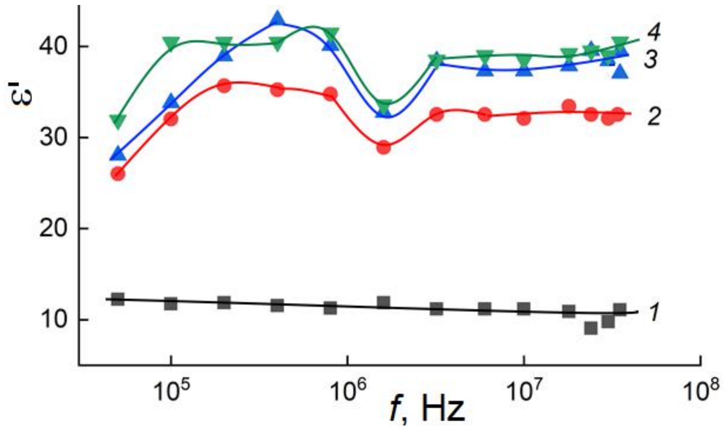

Fig. 1. Frequency dependences of the real component (ε') of the complex permittivity of single crystals of solid solutions $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ at x = 0 (1), 0.1 (2), 0.2 (3), 0.4 (4). T = 298 K.

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Figure 1 shows the frequency dependences of the real part of the complex permittivity $\varepsilon'(f)$ of $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ single crystals. It is evident that with increasing x the value ε' for $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ samples increases. The value ε'' also increased with increasing x in $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ single crystals.

Figure 2 shows the frequency dependences of the dielectric loss tangent (tanδ) in a $TlInS_2$ single crystal (curve *1*) and a $(TlInS_2)_{0.6}$ $(TlGaSe_2)_{0.4}$ solid solution (curve 2). The tanδ (f) dependences for $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ solid solutions of compositions $x = 0.1$ and 0.2 were located between curves *1* and *2*. In all cases, the tanδ (*f*) curves had a decreasing character with increasing frequency, which indicates losses of through conductivity [5] in the $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ crystals. With an increase in the $TlGaSe_2$ concentration, the dielectric losses in the $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ crystals increased.

Figure 3 shows the frequency dependences of the alternating current conductivity (*ac* conductivity) of $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ single crystals. For the $TlInS_2$ single crystal, the $\sigma_{ac}(f)$ dependence consisted of a long section $\sigma_{ac} \sim f^{\,0.8}$ up to the frequency $f = 10^7$ Hz, followed by a superlinear region with a further increase in frequency to $f = 3.5 \times 10^7$ Hz. In solid solutions $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$, the conductivity initially depended weakly on frequency. Starting with $f = 10^5$ Hz and up to 10^7 Hz, the dependence $\sigma_{ac}(f)$ described by the regularity $\sigma_{ac} \sim f^{\,0.8}$, which then turned into a superlinear section. The values of σ_{ac} of solid solutions $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ differed little from each other. But these values of σ_{ac} exceeded σ_{ac} of $TlInS_2$ single crystals by almost an order of magnitude.

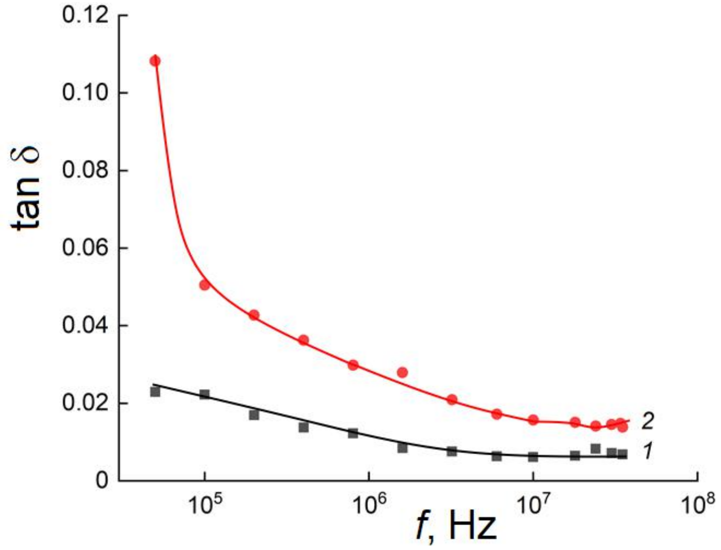

Fig. 2. Dependence of the tangent of the dielectric loss angle in $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ single crystals on the frequency at x = 0 (1), 0.4 (2). $T = 298$ K.

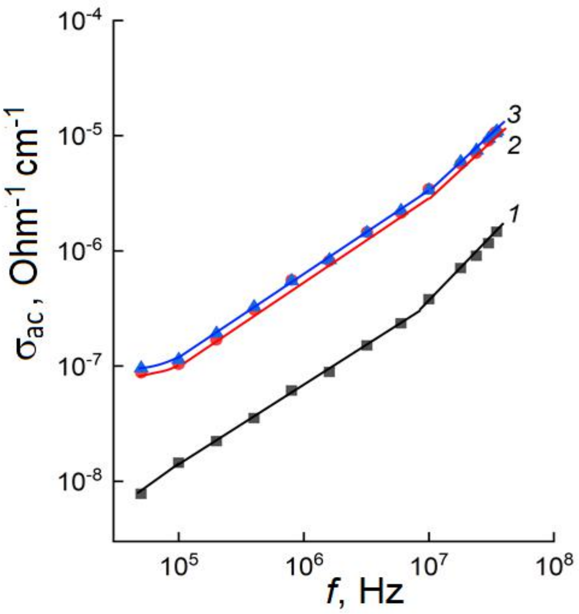

Fig. 3. Frequency-dependent conductivity on alternating current (*ac*-conductivity) of $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ single crystals at $x = 0$ (1), 0.1 (2), 0.4 (3). $T = 298$ K.

The experimental dependence $\sigma_{ac} \sim f^{0.8}$ obtained by us in single crystals of solid solutions $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ indicates that it is caused by jumps of charge carriers between states localized in the forbidden zone. These can be states localized near the edges of allowed zones, as well as states localized near the Fermi level [6]. Due to the fact that under experimental conditions the conductivity through states near the Fermi level always dominates over the conductivity through states near the edges of allowed bands, the law $\sigma_{ac} \sim f^{0.8}$ that we obtained indicates a hopping mechanism of charge transfer through states localized in the vicinity of the Fermi level.

For such a charge transfer mechanism, the following expression was obtained in [7]:

$$\sigma_{ac}(f) = \frac{\pi^3}{96} e^2 k T N_F^2 a^5 f \left[\ln\left(\frac{\nu_{ph}}{f} \right) \right]^4 ,$$

where e is the electron charge; k is the Boltzmann constant; N_F is the density of states near the Fermi level; $a = 1/\alpha$ is the localization radius; α is the decay constant of the wave function of a localized charge carrier; $\psi \sim e^{-\alpha r}$; ν_{ph} is the phonon frequency. According to this formula, the *ac* conductivity depends on the frequency as $f\left[\ln(\nu_{ph}/f)\right]^4$. The frequency range we use corresponds to the condition $f << \nu_{ph}$. Under this condition, the value of σ_a is approximately proportional to $f^{0.8}$. Using given formula, the density of states at the Fermi level was calculated from the experimentally found values of $\sigma_{ac}(f)$: $N_F = 5.8 \times 10^{18} - 1.6 \times 10^{19}$ eV^{-1}cm^{-3}.

The theory of hopping conductivity in alternating current allows us to determine the average hopping distance (R) of charge carriers between localized states in forbidden gap of $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ crystals: $R = 86$ Å. The average time of charge carrier jumps in $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$ crystals was determined to be $\tau = 2 \times 10^{-7}$ s.

Thus, with increasing concentration of $TlGaSe_2$ in $(TlInS_2)_{1-x}$ $(TlGaSe_2)_x$, the values of ε', ε'', tanδ and σ_{ac} of crystals increase. The frequency dispersion of these dielectric parameters also increases.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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