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Frequency dispersion of dielectric coefficients of $MnGaInTe_4$ crystals

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Abstract. The frequency and temperature dependences of the tangent of dielectric loss angle as well as the real and imaginary part of the dielectric constant of $MnGaInTe_4$ crystals are investigated in the frequency range of 10^2 to 10^6 Hz. The experimental values of the studied characteristics are determined. The real and imaginary parts of the permittivity are found to undergo significant dispersion, which has a relaxation nature. The main type of dielectric losses in $MnGaInTe_4$ crystals in the frequency range of 10^2 to 10^6 Hz are the electrical conductivity losses. The conductivity is characterized by a zone-hopping mechanism. The activation energies of charge carriers are determined.

Keywords: dielectric constant, dielectric loss, frequency, dispersion, relaxation, activation energy.

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1. Introduction

At present, chalcogenides with complex compositions have become the subject of extensive research due to their unusual physical properties and prospects for practical applications. Among these compounds, chalcogenides of the type AB_2C_4 (here A stands for Fe, Mn, Co or Ni, B stands for Ga or In, and C stands for S, Se or Te, respectively) are promising for creating new magnetic field controlled optoelectronic devices [1–20]. These compounds may be used for developing lasers, light modulators, photodetectors and other functional devices controlled by magnetic field. In [13], heterojunctions based on $FeIn_2Se_4$ nanocrystals [12] have been fabricated. Magnetoelectric effects (coupling of the magnetic and electrical subsystems) are known to take place in magnetic semiconductors. These effects are most intensely manifested in the systems permitting coexistence of magnetic order and electric polarization. In this respect, the need to study dielectric properties of magnetically ordered poorly conducting semiconductors becomes obvious. This problem is also relevant because electric polarization applied to a magnetically ordered state can significantly affect both the static and dynamic properties of the magnetic configuration in the system. In [21], a new semi-magnetic semiconductor compound – $MnGaInTe_4$ – was obtained and some of its physical properties were studied. In this research, the results of the study of frequency and temperature dependence of the tangent of dielectric loss angle as well as the real and imaginary part of the dielectric constant of $MnGaInTe_4$ crystals in the varying electric field are presented.

2. Experimental, results and discussion

$MnGaInTe_4$ compound was obtained from a 1:1 mixture of monoclinic $MnGa_2Te_4$ (space group *C*2/*c*) and tetragonal $MnIn_2Te_4$ (space group *I*-42*m*) phases. X-ray diffraction demonstrated that $MnGaInTe_4$ crystallized into tetragonal syngony with crystal lattice parameters $a = 6.10293$ Å and $c = 12.1766$ Å [21]. To measure the capacitance and tangent of dielectric loss angle, capacitors were prepared by applying silver paste to $MnGaInTe_4$ crystal plates with the thickness of ~1 mm and the measurements were carried out using an E7-20 (25...10^6 Hz) digital impedance measuring device. The crystals were placed in an adjustable cryostat capable of maintaining the temperature in the range of 293 to 400 K. The accuracy of temperature measurements was ± 0.5 K. The voltage across the sample was 1 V. The real and imaginary parts of the dielectric constant were calculated using the expressions $\varepsilon' = Cd/\varepsilon_0 S$ and $\varepsilon'' = \mathrm{tg}\delta\cdot\varepsilon'$, respectively.

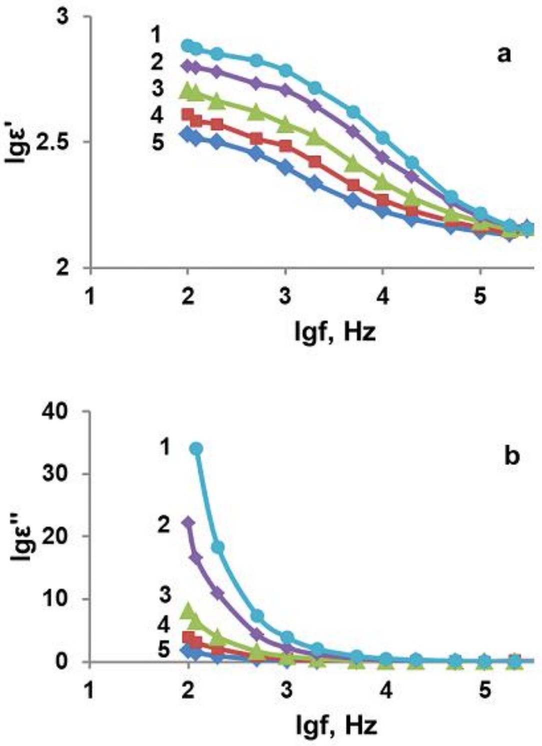

Fig. 1. ε′(*f*) (a) and (b) ε″ of the $MnGaInTe_4$ crystal *versus* lg *f* at different temperatures. *T*, K: 295.6 (*1*), 313 (*2*), 333 (*3*), 353 (*4*), and 363 (*5*).

Fig. 1a presents the frequency dependences of the real part of the dielectric constant (ε′) of the $MnGaInTe_4$ crystal measured at different temperatures. As can be seen from this figure, ε increases with temperature, which is related to the increase of the concentration of defects. The value of ε′ was determined to vary between 140 and 770 in the temperature range of 296.5 to 363 K and frequency range of $10^2…10^6$ Hz. It can be further seen from Fig. 1a that the frequency dependences of the real part of the dielectric constant are significantly dispersed. At the studied temperatures and the range of frequency $10^2…10^3$ Hz in the beginning ε′ slowly, then decreased rapidly at this range of $2\cdot10^3$ to 10 Hz by ε′. ε′ remains almost constant at frequencies between $2\cdot10^5$ and 10^6 Hz.

Fig. 1b shows the dependences of the imaginary part (ε″) of the dielectric constant of the $MnGaInTe_4$ crystal on electric field frequency measured at different temperatures. As can be seen from this figure, the dependences are monotonous in the frequency range of $10^2…10^6$ Hz, and ε″ significantly disperses at higher frequencies.

Fig. 2 shows frequency dependences of the conductivity of $MnGaInTe_4$ measured at different temperatures. It can be seen from this figure that the electrical conductivity varies as $\sigma \sim f^S (0.1 \le S \le 1.0)$ in the frequency range of $2\cdot10^2…10^6$ Hz. At 295.6 K, the exponent *S* takes values in the range of 0.10…0.79, while at 363 K it varies in the range of 0.05…0.65. The electrical conductivity *versus* frequency in crystalline and amorphous semiconductors obeys the law $\sigma(\omega) \sim \omega^S (0.1 \le S \le 1.0)$ [24]. Therefore, hopping conductivity may be suggested to occur in the $MnGaInTe_4$ crystals.

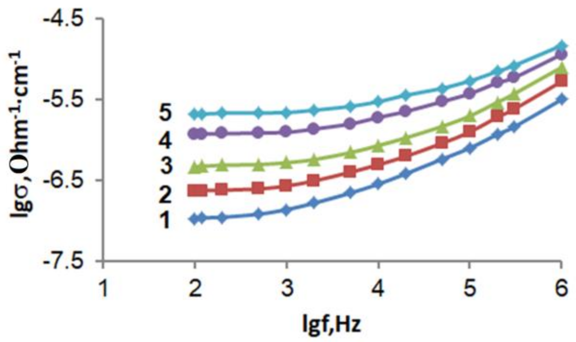

Fig. 2. Electrical conductivity *versus* frequency at different temperatures. *T*, K: 295.6 (*1*), 313 (*2*), 333 (*3*), 353 (*4*), and 363 (*5*).

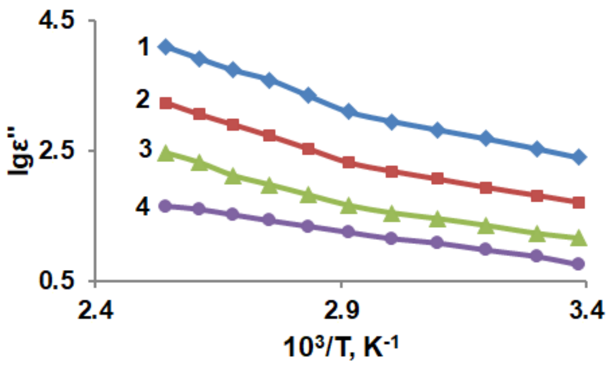

Fig. 3. lg ε″ *versus* $10^3/T$ at different frequencies for the $MnGaInTe_4$ crystal. *f*, Hz: 10^3 (*1*), $2…10^4$ (*2*), 10^5 (*3*), and 10^6 (*4*).

Temperature dependences of ε″ of the $MnGaInTe_4$ crystal at different frequency values are shown in Fig. 3. It can be seen from this figure that ε″ grows with temperature. The dependence of the imaginary part of the dielectric constant on electrical conductivity is known to have the form $\varepsilon'' = \frac{\sigma}{\varepsilon_0 \omega}$ [24], and the temperature dependence of ε″ has an activated character:

$$\varepsilon'' \sim \exp\left(-\frac{\Delta E}{kT}\right).$$

Here, *k* is the Boltzmann's constant and Δ*E* is the activation energy. Fig. 3 shows that ε″ decreases with the increase in frequency. A linear segment was found in the dependence $\lg \varepsilon'' \sim \frac{10^3}{T}$ (curve *4*) at the frequency of 10^6 Hz. The activation energy determined from this segment was equal to 0.22 eV.

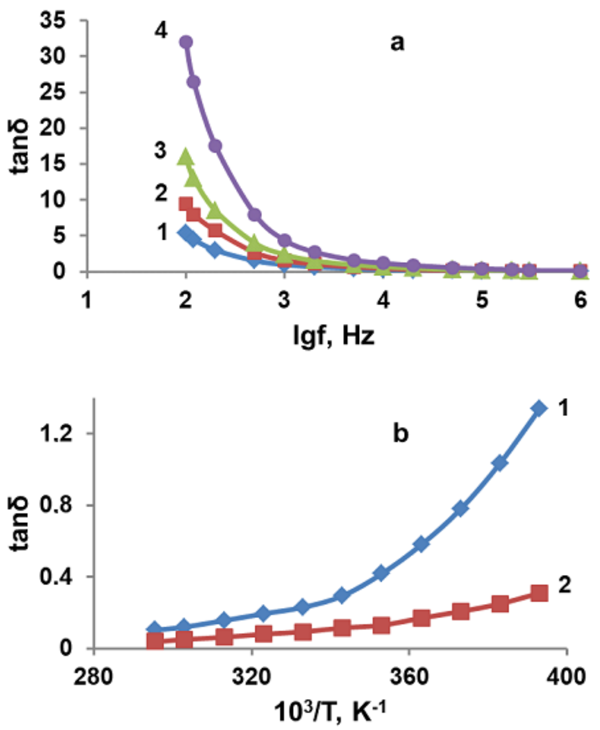

Fig. 4. a) tan δ *versus* lg *f* at different temperatures for the $MnGaInTe_4$ crystal. *T*, K: 295.6 (*1*), 313 (*2*), 333 (*3*), 353 (*4*), and 363 (*5*). b) tan δ *versus* *T* at the frequencies of 10^5 and 10^6 Hz for the $MnGaInTe_4$ crystal.

Furthermore, the dependences $\lg \varepsilon'' \sim \frac{10^3}{T}$ in the frequency range of 10^3 to 10^5 Hz consist of two straight lines having different trends. The activation energies were determined to be 0.30…0.22 eV in the low temperature range and 0.54…0.43 eV in the high temperature range. One may conclude that the value of activation energy is a function of frequency, which may be explained by the jump mechanism [23]. Moreover, the temperature dependence of the electrical conductivity of the $MnGaInTe_4$ crystal was found to have the activation nature [21], which means that this conductivity is characterized by the band hopping mechanisms.

Fig. 4a shows frequency dependences of the tangent of the dielectric loss angle (tan δ) of the $MnGaInTe_4$ crystal at different temperatures. The temperature dependences of tanδ at the frequencies of 10^5 and 10^6 Hz are shown in Fig. 4b. The tangent of the loss angle characterizes dielectric losses and is numerically equal to the ratio of the conduction current to the displacement current as follows [24]:

$$\tan \sigma = \frac{I_a}{I_r} = \frac{\sigma}{\varepsilon \varepsilon_0 \omega}.$$

Here, I_a is the active current, I_r – reactive current, $\omega = 2\pi f$ is the frequency, σ – electrical conductivity, ε is the real part of the dielectric constant, and ε_0 – electrical constant.

tan δ is a macroscopic characteristic of a dielectric. Its dependences on the frequency, temperature and other parameters of the electric field also characterize the dependences of the dielectric constant on these parameters.

It can be seen from Fig. 4a that the value of tan δ hyperbolically decreases when the frequency of the electric field increases. Such hyperbolic decrease indicates that loss of conductivity is the main type of dielectric loss in the $MnGaInTe_4$ crystal in the frequency range of 10^2 to 10^6 Hz [25]. The temperature dependence of tan δ is characterized by an exponential increase due to the increase in conductivity. Therefore, electrical conductivity significantly contributes to tan δ at high temperatures and low frequencies [24].

3. Conclusions

In this work, the results of the experimental study of the dielectric characteristics of a $MnGaInTe_4$ crystal in an alternating electric field are presented. A significant dispersion of the real and imaginary part of the dielectric constant corresponding to the relaxation nature is found out. The main type of dielectric loss in the $MnGaInTe_4$ crystal in the frequency range of 10^2 to 10^6 Hz is the loss due to electrical conductivity. It was found as well that conduction in the $MnGaInTe_4$ crystal in the frequency range of 10^2 to 10^6 Hz takes place according to the jumping mechanism. The activation energies of charge carriers are determined from the dependences $\lg \varepsilon'' \sim \frac{10^3}{T}$. The activation energy values at low temperatures vary in the range of 0.30 to 0.22 eV, and at high temperatures they change in the range of 0.54 to 0.43 eV.

Conflict of interests

The authors declare that they have no conflict of interest.

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Mammadov F.M.: investigation, resources, validation, visualization, calculations, writing – review & editing.
Muradov M.B.: methodology, conceptualization, validation, writing – review & editing.

Дисперсія частоти діелектричних коефіцієнтів кристалів $MnGaInTe_4$

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Анотація. Досліджено частотні та температурні залежності тангенса кута діелектричних втрат, а також дійсної та уявної частин діелектричної проникності кристалів $MnGaInTe_4$ в діапазоні частот $10^2…10^6$ Гц. Визначено їх експериментальні значення. Виявлено, що дійсна та уявна частини діелектричної проникності зазнають значної дисперсії, яка носить релаксаційний характер. Основним видом діелектричних втрат у кристалах $MnGaInTe_4$ у діапазоні частот $10^2…10^6$ Гц є втрати на електропровідність, а провідність характеризується зонно-стрибковим механізмом. Визначено енергії активації носіїв заряду.

Ключові слова: діелектрична проникність, діелектричні втрати, частота, дисперсія, релаксація, енергія активації.