

PACS: 75.30.Hx

ISSN 1729-4428 (Print)
ISSN 2309-8589 (Online)

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Faraday Effect in ZnSe Crystals Doped with Transition Metals

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The Faraday effect in zinc selenide crystals doped with transition metal impurities has been investigated. It has been established that magnetic impurities cause the formation of right- and left-handed components of circular polarisation of radiation due to the interaction of charge carriers with ions of the crystal lattice. In a longitudinal magnetic field, this leads to the appearance of different spectral components of radiation and the rotation of the plane of polarisation of light. The dispersion dependencies of the Verdet constant for the studied samples were determined. It has been shown that doping ZnSe base substrates with Mn and Co impurities leads to the formation of a paramagnetic state, while Fe impurities cause the appearance of ferromagnetic properties in the material.

Keywords: zinc selenide, 3D impurities, Faraday effect, Verde constant, magnetic properties.

Received 20 March 2026; Accepted 02 September 2026; Published 16 September 2026.

Introduction

Wide-bandgap II–VI compound semiconductors attract considerable attention from researchers due to their unique electronic and optical properties, which open up broad opportunities for the creation of modern optoelectronic and photonic devices. Among such materials, zinc selenide (ZnSe) occupies a special place, characterised by a direct bandgap structure and a large bandgap width. Thanks to these properties, ZnSe is a promising material for the manufacture of light-emitting diodes, laser radiation sources, photodetectors and other devices operating in the short-wave blue-blue region of the spectrum [1,2].

It is known that the physical properties of ZnSe can change significantly due to the introduction of various impurities. Doping with elements of groups I, III, V, and VII of the periodic table allows controlling the electrical and optical characteristics of the material, which is important for characterising the parameters of semiconductor devices. Of particular interest is doping with isovalent impurities, which contributes to increasing the temperature and radiation stability of the material, as well as ensuring effective generation-recombination processes with high quantum efficiency of radiation [3,4].

The doping of ZnSe with transition metal impurities

is of particular scientific and practical interest. In this case, so-called diluted magnetic semiconductors can be formed, which are characterised by strong exchange interactions between localised magnetic moments of transition metal ions and charge carriers in the allowed energy zones. Such interaction significantly affects the electronic structure of the material and can lead to the emergence of various magnetic states – diamagnetic, paramagnetic or ferromagnetic, depending on the type and concentration of the impurity [5–7]. The study of such materials is important not only for fundamental semiconductor physics, but also for the development of new areas of electronics, in particular magneto-optics and spintronics.

One of the effective methods for studying the interaction of charge carriers with magnetic impurities is the analysis of magneto-optical phenomena. Such phenomena include the Faraday effect, which consists in the rotation of the polarisation plane of linearly polarised light as it passes through a substance in a longitudinal magnetic field. The spectral dependencies of the Verdet constant, which characterises the amount of rotation of the polarisation plane, contain important information about the electronic structure of the material, the nature of interband and intracentre transitions, as well as the role of impurity centres and crystal lattice defects in the formation of the optical and magnetic properties of

semiconductors [8–12].

Despite a significant number of studies on the magneto-optical properties of II–VI group semiconductors, the influence of transition metal impurities on the formation of the Faraday effect in ZnSe crystals has not been sufficiently studied. In particular, the peculiarities of the spectral behaviour of the Verdet constant and the relationship between the type of magnetic impurity and the magnetic state of the material require further study.

In this regard, the aim of this work is to study the Faraday effect in ZnSe crystals doped with 3d transition metal impurities (Mn, Fe, Co) and to establish the patterns of change in their magneto-optical properties.

I. Samples and Experimental Methods

ZnSe plates measuring $4 \times 4 \times 1$ mm³, cut from bulk crystals, served as the base substrates. The latter were obtained from a melt of stoichiometric composition under inert gas pressure. These specially unalloyed ZnSe crystals are characterised by fairly high concentrations ($\sim 10^{20}$ cm⁻³) of cationic V_{Zn} and anionic V_{Se} vacancies, which are deep acceptors and shallow donors, respectively [13]. At the same time, at room temperature, the base substrates have a fairly low electronic conductivity ($\sigma_n \leq 10^{-9}$ Ohm⁻¹·cm⁻¹). It was determined using a standard method for this type of research [14].

To obtain ZnSe layers with 3d impurities, the closed-volume diffusion method was chosen. For this purpose, after preliminary treatment, the substrates were placed in a quartz ampoule together with a sample of one of the 3d elements of semiconductor purity. Their amount was determined by the condition of saturated vapour formation at the maximum annealing temperature T_a^m . Along with the 3d element, a charge of elemental selenium was also loaded into the ampoule. Its weight ensured the creation of excess pressure, which prevents erosion of the substrate surface. In the experiment, after diffusion, the surface remains mirror-like, which is important for further optical studies (without additional processing). It is also important with this amount of Se to prevent the 3d element from entering the anion sublattice (Se sublattice). Under these conditions, the condition for the entry of impurities into cationic (zinc) nodes is realised, which is a fundamental condition for the substitution of 3d elements when doping III-V and II-VI compounds with them [15–18].

Spectral characteristics were determined using known methods [19,20]. An MDR-23 diffraction device was used as a spectral device, and photodetectors ensured reliable signal registration in the spectral range of 0.82–0.27 μm.

II. Discussion of the Experimental Results

As is known [14], the Faraday effect consists in the rotation of the plane of polarisation when linearly polarised light passes through a substance located in a longitudinal magnetic field. In the approximation of classical electron dispersion, this process is caused by the difference in the phase velocities of light waves of left and

right circular polarisation as they propagate along the magnetic field in the material. Accordingly, the angle of rotation of the plane of polarisation is [21,22]

$$\Theta = V \cdot H \cdot d, \quad (1)$$

where H is the magnetic field strength; d is the thickness of the sample; and V is the Verdet constant, which in turn depends on the frequency of light and the nature of the substance.

In the Faraday effect, the magnetic field splits the energy levels of atoms according to the Zeeman effect, accompanied by the appearance of new electronic transitions. In wide-bandgap semiconductors, such transitions are interband, exciton, and intraband. Impurity and intrinsic lattice defects also play an important role in the formation of transitions. The contribution of each of them is determined by many factors, among which the most important are the parameters of the material, the conditions of the experiment (temperature, magnetic field strength, light wavelength, etc.), the type and concentration of magnetic impurities. They affect the nature of the interaction of charge carriers in the allowed energy zones with the ions of the substance and thus affect the rotation of the polarisation plane. Accordingly, so-called semi-magnetic semiconductors [17] are of particular importance. Their characteristic feature is the ability, depending on the magnetic component content and the experimental temperature, to cause the formation of diamagnetic, paramagnetic or ferromagnetic states.

The Faraday effect in ZnSe is investigated and the influence of transition metal impurities Mn, Fe, and Co on the rotation of the polarisation plane is analysed. Fig. 1 shows the spectral dependencies (dispersion curves) of the Verdet constant, which was calculated using equation (1). The study of the angle of rotation of the polarisation plane was carried out at $T = 77$ K and a field strength of $H = 10000$ V/m with a sample thickness of $d_0 \approx 0.1$ cm.

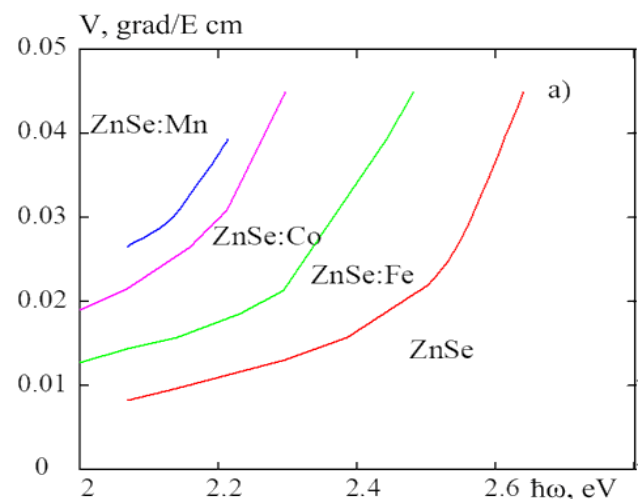


Fig. 1. Spectral dependencies of the Verdet constant calculated using equation (1).

An increase in the constant Verda with an increase in the energy of the light quantum is observed for all studied samples, which is characteristic of the diamagnetic state

of matter [18,22]. The transition metal impurity is not distributed throughout the entire volume of the sample, but, in accordance with the laws of diffusion layer formation, covers a certain diffusion layer with a thickness d [15]. Its value is less than the thickness of the studied sample d_0 . Accordingly, in order to establish a reliable spectral dependence of the Verdet constant in doped samples, it is necessary to determine the difference between the values of the Verdet constant V for doped ZnSe: Me and its value at the same photon energy $\hbar\omega$ for basic ZnSe crystals. The obtained values are shown in Fig. 2.

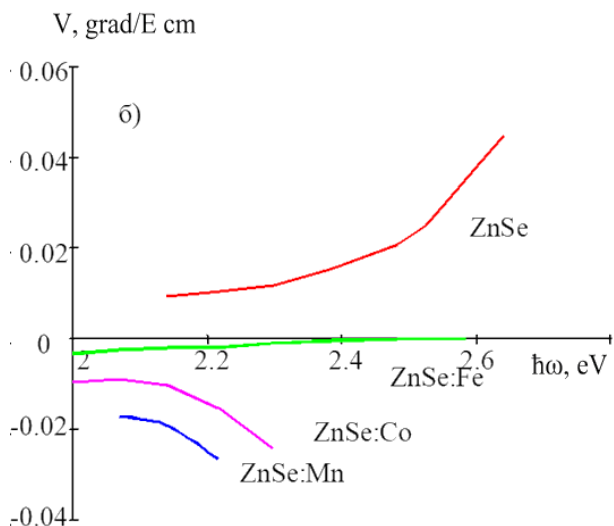


Fig. 2. Spectral dependencies of the Verdet constant.

Characteristic dispersion curves of the Verdet constant dependence on photon energy $V(\hbar\omega)$ are observed. Their nature is determined by the corresponding magnetic state of the doped material. It is necessary to note the shift of the spectral interval, as well as the change in the sign of the value, namely, a negative value. All dependencies are characterised by an increase in the Verdet constant with an increase in the energy of the light quantum. For the base unalloyed substrate, the $V(\hbar\omega)$ dependence is characterised by a nonlinear nature with a fairly rapid change in the Verdet constant. Such properties are characteristic of the diamagnetic state of matter. Doping zinc selenide with Mn and Co impurities brings them into a paramagnetic state, which is confirmed by a change in the sign of magnetisation. When alloyed with Fe, the value of the Verdet constant decreases with an increase in the energy of the light quantum and the degree of change in the value of $V(\hbar\omega)$. Such properties are characteristic of the ferromagnetic state of matter [17,18].

Thus, basic unalloyed ZnSe crystals are typical materials with diamagnetic properties. Dispersion curves of the Verdet constant dependence on photon energy $V(\hbar\omega)$ are characterised by a nonlinear increase in the constant with increasing photon energy. Doping basic zinc selenide substrates with transition metal elements Mn and Co brings them into a paramagnetic state, and Fe into a ferromagnetic state. This is evidenced by a change in the sign of magnetisation. For the ferromagnetic state, a linear

dependence of magnetisation on photon energy is observed.

Conclusions

The work experimentally investigates the Faraday magneto-optical effect in ZnSe crystals doped with 3d impurities of transition metals Mn, Fe, and Co, and establishes the peculiarities of the formation of their magneto-optical properties in comparison with the known literature data [17,18] for other materials.

1. For the first time, spectral dependencies of the Verdet constant in a wide range of photon energies at liquid nitrogen temperature were determined for ZnSe crystals with diffusion-introduced transition metal impurities. It has been shown that unalloyed ZnSe crystals are characterised by a nonlinear dispersion dependence of the Verdet constant typical for diamagnetic materials, with its value increasing with increasing photon energy.

2. It has been established that the introduction of magnetic 3d impurities significantly modifies the magneto-optical properties of zinc selenide. Mn and Co doping leads to the formation of a paramagnetic state of the material, which manifests itself in a change in the nature of the dispersion dependencies of the Verdet constant and the appearance of specific features in the spectral region of the study.

3. It has been shown that doping ZnSe with Fe impurities causes the formation of a ferromagnetic state in the diffusion layer, accompanied by a change in the sign and nature of the spectral dependence of the Verdet constant. The results obtained indicate the significant role of exchange interaction between localised magnetic moments of 3d ions and charge carriers in the formation of the magneto-optical properties of the material.

4. The established patterns of change in the Verdet constant depending on the type of magnetic impurity confirm the possibility of controlling the magnetic state and magneto-optical parameters of ZnSe crystals by controlled doping with transition metals.

5. The results obtained expand our understanding of the mechanisms of magneto-optical effects in semimagnetic semiconductors based on II–VI compounds and indicate the promise of using doped ZnSe crystals in magneto-optical modulators, magnetic field sensors, and other elements of modern optoelectronics.

Acknowledgments.

The research of T.M. Mazur was funded by the National Research Foundation of Ukraine (project 2025.07/0427, “Newest complex probabilistic methods for studying asymptotic properties of analytical solutions of differential equations represented by multiple random series and integrals and their potential applications”, 0126U002547).

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Ефект Фарадея в кристалах ZnSe, легованих перехідними металами

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Досліджено ефект Фарадея в кристалах селеніду цинку, легованих домішками перехідних металів. Встановлено, що магнітні домішки зумовлюють формування правої та лівої компонент колової поляризації випромінювання внаслідок взаємодії носіїв заряду з іонами кристалічної ґратки. У поздовжньому магнітному полі це призводить до появи різних спектральних компонент випромінювання та обертання площини поляризації світла. Визначено дисперсійні залежності сталої Верде для досліджуваних зразків. Показано, що легування базових підкладинок ZnSe домішками Mn і Co приводить до формування парамагнітного стану, тоді як домішка Fe зумовлює появу феромагнітних властивостей матеріалу.

Ключові слова: селенід цинку, 3d-домішки, ефект Фарадея, стала Верде, магнітні властивості.