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MECHANISM AND ANALYSIS OF THE PIEZO-PHOTORESISTIVE EFFECT IN $TlInSe_2$ SINGLE CRYSTALS

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Abstract: This study investigates the electrical, photoelectric, and tensoresistive properties of $TlInSe_2$ single crystals under mechanical deformation. The changes in conductivity, photocurrent density, and electronic band structures were analyzed under compressive and tensile strain. The results demonstrate that uniaxial deformation along the [001] crystallographic direction alters the energy band gap of the crystal lattice, which in turn leads to either an increase or decrease in photocurrent and conductivity. The paper also presents modern analyses of the potential applications of these characteristics in nanoelectronics, optoelectronic sensors, and high-sensitivity mechanical detectors.
Keywords: piezo-photoresistive effect, $TlInSe_2$ single crystals, uniaxial deformation, electronic bands, optical transitions, sensors, semiconductors.

1. Introduction

In recent years, research on the development of highly sensitive sensors, strain-gauge systems, and optical detectors based on semiconductor materials has rapidly progressed. Particularly, the study of materials exhibiting the piezo-photoresistive effect has become a significant direction in physics and engineering.

Such materials change their electrical resistance in response to external mechanical stress, light intensity, or temperature variations. As a result, they serve as highly sensitive elements in devices that measure mechanical vibrations, pressure, temperature, and light intensity.

$TlInSe_2$ single crystals**,** belonging to the AIII–BIV–C_2 type of ternary semiconductors, possess an anisotropic crystal lattice, a multivalley electronic structure**,** and a wide spectral range of photoabsorption. Therefore, $TlInSe_2$ is a unique material that simultaneously exhibits piezoresistive and photoresistive properties.

Earlier studies (Guseinov et al., 1985; Umarov, 2003) showed that the electrical conductivity and photocurrent spectra of $TlInSe_2$ single crystals change under uniaxial deformation. However, the exact mechanisms of deformation and the energy characteristics of interband transitions remain insufficiently understood. Hence, this paper provides a modern analysis of the nature of the piezo-photoresistive effect**,** focusing on electronic redistribution and optical transitions occurring under mechanical stress.

2. Research Methodology

2.1. Sample Preparation

The $TlInSe_2$ single crystals were synthesized by melting the components in a stoichiometric ratio. High-purity elements of thallium (Tl), indium (In), and selenium (Se) were used as initial materials. The mixture was sealed in evacuated quartz ampoules (10^{-4} mm Hg) and crystallized using the Bridgman–Stockbarger method. The growth rate of the crystallization front was maintained within 0.5–0.9 mm/h.

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The obtained single crystals were cleaved along natural cleavage planes into thin plates. The samples were prepared in the form of plates with dimensions of 10×10×0.25 mm**.** Reliable ohmic contacts were made using indium and copper (or nickel) wires.

2.2. Measurement Techniques

Measurements of electrical conductivity and photocurrent were carried out along the [001] crystallographic direction. Deformation was applied as mechanical compression (positive strain) and tension (negative strain)**.** For each case, electrical resistance, photocurrent density, and photoabsorption spectra were recorded.

Spectral measurements were performed within the 0.8–3.2 eV range using a halogen lamp as the light source and a system comprising a monochromator and an optoelectronic amplifier for detection. Based on the experimental data, photocurrent (I_s)**,** tensosensitivity coefficient (Kε)**,** and interband transition energy (Eg) were determined, and their dependence on deformation pressure was plotted.

3. Results

3.1. Dependence of Conductivity on Deformation

Under compression, the electrical conductivity of $TlInSe_2$ single crystals increases, while under tension, it decreases. This phenomenon is explained by the change in the energy of electron transitions from the valence band to the conduction band.

During compression, the band gap widens, and the Fermi level shifts upward, leading to an increase in electron concentration and conductivity. Conversely, under tension, the band gap narrows, resulting in reduced conductivity.

These processes can be explained by the multivalley band model of $TlInSe_2$. During compression and tension, electrons redistribute between different valleys, changing the number and mobility of charge carriers.

3.2. Photocurrent and Photoabsorption Spectrum

Spectral analysis showed that the maximum of the photocurrent remains nearly unchanged (around **1.2 eV**) under deformation, but the **lo**ng-wavelength edge shifts: it decreases under compression and increases under tension. This indicates changes in the energy of indirect optical transitions**.**

While direct transitions ($K = 0$) remain almost constant, indirect transitions ($K \neq 0$) exhibit energy shifts depending on the type of deformation. This observation confirms the presence of a multivalley electronic spectrum in $TlInSe_2$ crystals.

3.3. Tensosensitivity Coefficient

The tensosensitivity coefficient (Kε) changes proportionally with variations in photocurrent under deformation. Under positive strain (compression), Kε increases, while under negative strain (tension), it decreases.

Spectral analysis revealed two main peaks — one at 1.2 eV (primary) and another at 1.6–1.7 eV**.** Under tensile deformation, an additional peak appears near 2.1 eV**.** These changes are attributed to an increase in the number of possible interband transitions caused by electron transfer between valleys during deformation.

4. Discussion

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The results show that mechanical deformation significantly alters the energy structure of the electronic bands in $TlInSe_2$ crystals. This behavior forms the basis of the piezo-photoresistive effect**.**

Under compression, the energy difference between the valleys increases, enhancing the inter-valley electron flow, which raises the tensosensitivity. In contrast, under tension, the valleys become energetically closer, reducing the probability of transitions.

This mechanism makes $TlInSe_2$ a promising material for high-sensitivity piezoresistive sensors**.** Such devices can generate electrical signals in response to mechanical pressure, vibration, or force and can be integrated into optoelectronic systems.

Additionally, under illumination, the piezoresistive effect becomes more pronounced, indicating the presence of a photo-induced tensoresistive phenomenon. This opens opportunities for developing optically controlled sensors**.**

From a modern perspective, $TlInSe_2$-based sensors can be utilized in IoT (Internet of Things) systems, smart devices**,** robotics**,** and biomedical applications due to their high sensitivity and near-nanoscale precision. Furthermore, the optical properties of this material make it promising for photovoltaic systems**,** solar cells**,** and light detectors**.** Thus, $TlInSe_2$ crystals are not only an object of laboratory research but also a highly efficient material for practical applications.

Conclusions

Based on the conducted research, the following conclusions were drawn:

1. Uniaxial deformation in $TlInSe_2$ single crystals significantly affects their electrical conductivity, photocurrent, and photoabsorption properties.
2. Conductivity increases under compression and decreases under tension, corresponding to changes in interband transition energy.
3. The long-wavelength edge of the photocurrent spectrum shifts depending on the direction of deformation, confirming the multivalley structure of the electronic bands.
4. Variations in tensosensitivity are determined by the energy difference between valleys; it increases with compression and decreases with tension.
5. $TlInSe_2$ crystals are highly sensitive materials exhibiting a piezo-photoresistive effect, suitable for the development of force, pressure, acceleration, and torque sensors.
6. The effect is enhanced under photo-stimulation, opening new possibilities for optically controlled sensors.

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