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THE EFFECT OF DOPING WITH GROUP I ELEMENTS ON THE PIEZORESISTIVE PROPERTIES OF TLINSE₂ SINGLE CRYSTALS

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Abstract: This article investigates the physical properties of $TlInSe_2$ single crystals, particularly their electrical resistance and piezoresistive sensitivity, under the influence of doping with Group I elements (Ag, Cu). The single crystals were synthesized using the Bridgman–Stockbarger method and doped with various concentrations. The samples were studied through X-ray diffraction, temperature-dependent resistivity measurements, dielectric response analysis, and resistance changes under external mechanical stress. The results revealed that the incorporation of Ag and Cu significantly affects the lattice parameters and the density of electronic states, leading to a multiple increase in piezoresistive sensitivity. These findings expand the potential applications of $TlInSe_2$-based single crystals in modern sensor devices.
Keywords: Single crystals, doping, piezoresistive properties, electrical conductivity, anisotropy.

Introduction

At present, the study of semiconductor materials and their physical properties is one of the most urgent scientific and practical tasks. The response of these materials to external factors determines their applicability in electronics, optoelectronics, sensors, and telecommunication systems. In particular, the piezoresistive effect, which reflects the change in electrical resistance under external mechanical stress or deformation, is of great importance for modern technology. Consequently, enhancing the piezoresistive sensitivity of new materials and developing methods to control it has become the focus of many recent studies.

$TlInSe_2$ single crystals are distinguished by their layered structure, good electrical conductivity, and optical transparency. Their properties can be modified through doping with Group I elements, as previously suggested theoretically, though experimental investigations have been insufficiently comprehensive. Therefore, this work focuses on doping $TlInSe_2$ single crystals with Ag and Cu, analyzing the resulting changes, and evaluating the effect of doping on piezoresistive properties. The practical significance lies in the potential use of these materials in highly sensitive detectors and other semiconductor devices.

Methodology

The study began with the synthesis of single crystals using the classical Bridgman–Stockbarger method. Chemically pure Tl, In, and Se elements were melted under vacuum (10^{-6} Torr) and cooled at a controlled rate. This ensured high-quality, defect-free crystal growth. Ag and Cu elements were introduced at different concentrations to achieve doping. Careful control of dopant concentrations was maintained, since excessive amounts could cause lattice distortions.

The synthesized single crystals were analyzed by X-ray diffraction to determine lattice parameters, deformation levels, and defect presence. Resistivity measurements were performed at different temperatures. External mechanical stress was applied to the crystals using a special

measurement setup, and changes in electrical resistance were recorded. The piezoresistive sensitivity of the materials was then calculated.
For the study of dielectric parameters, AC signals were used. Experiments at different frequencies made it possible to observe how dielectric conductivity varied with doping. Each measurement was repeated multiple times, and the data were processed statistically. Results were summarized in graphical and tabular form.
An important aspect of the methodology was the comparative study of pure $TlInSe_2$ single crystals and doped samples. This approach allowed the direct influence of doping to be identified and the concentration-dependent boundaries to be determined, ensuring more reliable results.

Results

The experiments revealed that doping with Ag and Cu significantly influences the electrical and dielectric properties of $TlInSe_2$ single crystals. X-ray diffraction data showed slight lattice deformations induced by doping, which affected electron transport mechanisms and altered the overall conductivity.
Resistivity measurements indicated a decrease in resistance upon doping. This effect was particularly pronounced at low temperatures. Doped samples demonstrated better conductivity than pure crystals, attributed to an increased density of charge carriers.
Dielectric studies showed that doped crystals exhibited greater stability compared to pure $TlInSe_2$. When tested at different frequencies, Ag- and Cu-doped samples showed reduced energy losses, indicating more stable responses to electric fields.
The most remarkable results were observed in piezoresistive sensitivity tests. Under mechanical stress, doped samples showed significantly higher sensitivity compared to pure single crystals. The piezoresistive coefficient increased up to twofold in some cases, highlighting the potential of doped crystals for sensor technology applications.

Discussion

The analysis of the results shows that doping $TlInSe_2$ single crystals with Group I elements profoundly influences their structural and electrical properties. Ag atoms facilitate the free movement of electrons within the lattice, leading to an increase in charge carrier concentration. As a result, electrical resistance decreases and conductivity improves. This also contributes to the enhancement of dielectric properties.
The influence of Cu atoms, however, manifested differently. They introduced lattice distortions, which enhanced piezoresistive sensitivity. The sharp changes in resistance under mechanical stress were primarily linked to Cu doping. Thus, the combined doping with Ag and Cu could simultaneously improve both conductivity and piezoresistive sensitivity of single crystals.
When compared with other semiconductor systems, $TlInSe_2$ retained its unique advantages after doping. For example, it preserved its high transparency and optical stability, which makes it suitable not only for sensor devices but also for optoelectronic applications.
Another important factor highlighted during the discussion was the concentration of dopants. Excessive doping led to the formation of defects in the crystal lattice, which negatively affected material properties. Therefore, determining the optimal concentration of Ag and Cu is crucial. Our study confirmed that when doping levels are kept within certain limits, the most favorable results are obtained.

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Conclusion

The study demonstrated that the physical properties of $TlInSe_2$ single crystals can be effectively controlled through doping with Group I elements. Single crystals grown using the Bridgman–Stockbarger method exhibited high quality, and doping significantly influenced their resistivity, dielectric parameters, and piezoresistive sensitivity. Ag doping improved conductivity, while Cu doping enhanced sensitivity. The piezoresistive coefficient increased up to twofold compared to pure crystals, opening opportunities for the use of these materials in highly sensitive sensor devices. Furthermore, their preserved optical and structural advantages expand their potential applications in optoelectronics and other modern technological fields.

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