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Influence of Elastic Deformations and Temperature on the Tensoresistive Properties of the Compound TlIn$_{1-x}$Co$_x$Se$_2$ (0 ≤ X ≤ 0.5)

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Abstract: The paper presents the results of studying the influence of various external physical factors, including elastic deformations and temperature, on the tensoresistive mechanisms of single crystals of solid solutions TlIn$_{1-x}$Co$_x$Se$_2$ (0 ≤ x ≤ 0.5). The effect of temperature on the strain sensitivity of TlIn$_{1-x}$Co$_x$Se$_2$ single crystals in the cobalt concentration range 0 ≤ x ≤ 0.5 was determined. A mode of synthesis and growth of single crystals of solid solutions TlIn$_{1-x}$Co$_x$Se$_2$ (0 ≤ X ≤ 0.5) by the improved Bridgman-Stockbarger method with the use of electronic temperature controllers was developed to maintain the optimal thermal regime during crystallization. The directional crystallization rate was about 0.9 mm/h. TlIn$_{1-x}$Co$_x$Se$_2$ single crystals had p-type conductivity. The samples for the study were made by cleaving single crystals in two mutually perpendicular planes of a natural cleavage and had the shape of a rectangular parallelepiped. The dimensions of the studied samples were 10x10x0.25 mm^3. Ohmic contacts are obtained by spot welding of the corresponding wires (ø = 0.01 mm) by a capacitor discharge on the ends of samples heated in an inert gas flow. A technique has been developed for strain gauge measurements in a static mode at a temperature of 300–400 K. The study of tensoresistive mechanisms of TlIn$_{1-x}$Co$_x$Se$_2$ solid solution single crystals has led to very interesting results. First of all, it should be emphasized that these crystals exhibit a strong piezoresistive effect in the direction of the [001] crystallographic axis, which, in combination with their mechanical, elastic, crystallographic and other features, makes them very promising materials for creating new miniature highly sensitive and reliable electromechanical transducers.

Keywords: Monocrystals, Tenzoresistive Characteristics, Solid Solutions, Tenzosensitivity of Crystals, Electromechanical Transformers

1. Introduction

To date, silicon and germanium are the most widely used materials in semiconductor electronics. This is due to the wide distribution of silicon on earth, the proximity of the structure of germanium and silicon, the unique properties of these materials and, as a result, the best knowledge of their physicochemical characteristics.

However, the needs of modern electronics and nanotechnology are not satisfied only by these materials and require materials with a variety of properties. Therefore, along with the improvement of the properties of existing ones, the search for new semiconductor materials and the

study of their various characteristics is currently one of the cardinal general tasks of modern semiconductor physics and leads to the discovery of many semiconductor materials, including ternary and more complex compounds. The discovery of new materials, the study of the relationship between the composition, structure and properties of multicomponent semiconductor compounds, in addition to deepening fundamental scientific ideas about semiconductors, also opens up new perspectives: new compounds, as a rule, exhibit new qualities and, thereby, contribute to the solution of necessary technical problems.

Among semiconductor crystals, a special place is occupied by layered and chain semiconductors with their inherent

strong anisotropy of physical properties along different crystallographic directions.

According to the above, in recent years, interest in semiconductor strain gauges has increased dramatically. The reasons that caused such a rapid development of semiconductor strain gauges lie in the new wide possibilities that semiconductor strain gauges open up for experimenters working in the aviation and oil refining industries to study the strength of materials, designs for designers, nanotechnological transducers of mechanical quantities (force, pressure, moment, etc.) into electrical signals.

So far, the physical mechanisms of the tensoresistive property of crystals of multicomponent semiconductor compounds of the A^{III}B^{III}C$_2^{VI}$ type and solid solutions based on them remain poorly understood. An important stimulus to the study of semiconductors with a strongly anisotropic structure is their increasing practical importance.

The strong anisotropy of the chemical bonding forces between atomic complexes in the low-symmetry crystal structure of complex compounds TlIn$_{1-x}$Co$_x$Se$_2$, in some cases (the structure contains chain structures), in the study of their physical properties, predetermines the specific features due to which these compounds become objects for model representations.

The study of tensoresistive mechanisms of single crystals of TlIn$_{1-x}$Co$_x$Se$_2$ solid solutions in this respect led to very interesting results. First of all, it should be emphasized that these crystals show a strong piezoresistive effect in the [001] direction, which, in combination with their mechanical, elastic, crystallographic and other features, makes them very promising materials for creating new miniature highly sensitive and reliable electromechanical transducers.

Therefore, the purpose of our study was to study the influence of various external physical factors, including elastic deformations and temperature, on the tensoresistive properties of the TlIn$_{1-x}$Co$_x$Se$_2$ compound.

2. Experimental Technique

Alloys of a given composition were synthesized by fusing components in accordance with stoichiometry in evacuated to a pressure of 1.2×10^{-4} mm. rt. Art. quartz ampoules with a diameter of 12 - 15 mm, a melt height of 50 - 60 mm, especially pure elements were used as initial components: thallium 000, indium 000, cobalt 000, sulfur of high purity - 16 - 5 and selenium of high purity - 17 – 4.

Single crystals were grown by the improved Bridgman-Stockbarger method with the use of electronic thermostats to maintain the optimal thermal regime during crystallization. The directional crystallization rate was about 0.9 mm/h. TlIn$_{1-x}$Co$_x$Se$_2$ single crystals had p-type conductivity. Samples for research were made by cleaving single crystals in two mutually perpendicular planes of natural cleavage and had the shape of a rectangular parallelepiped. The dimensions of the studied samples were 10x10x0.25 mm^3.

Ohmic contacts are obtained by spot welding of the corresponding wires (ø = 0.01 mm) by a capacitor discharge on the ends of samples heated in an inert gas flow [1-3].

The strain sensitivity of the samples was measured in the temperature range of 300-410 K in the static mode specified by the technique in [4].

3. Results of the Study and Their Discussion

The paper reports the results of our study of the effect of directional deformation on the tensoresistive properties of TlIn$_{1-x}$Co$_x$Se$_2$ solid solutions, on the basis of which an assumption was made about the most probable locations of extreme in the Brillouin zone. It is shown that TlIn$_{1-x}$Co$_x$Se$_2$ single crystals, due to their high strain sensitivity, significant flexibility and the ability to chip onto the desired filamentous plates with mirror faces in the direction of the maximum piezoresistive effect, are extremely effective materials for semiconductor strain gauges. The obtained new TlIn$_{1-x}$Co$_x$Se$_2$ single crystals satisfy the basic general requirements of semiconductor strain gauges: - if possible, a high coefficient of strain sensitivity; linear dependence of resistance change with deformation; no hysteresis characteristics; minimal sensitivity to the influence of side external physical factors.

The parameters listed above are determined mainly by the properties of the semiconductor material itself, although they can also be significantly influenced by the technology of manufacturing strain gauges.

To emphasize the uniqueness of the proposed new material TlIn$_{1-x}$Co$_x$Se$_2$, first of all, we note that their characteristics should be compared with the parameters of the known and most widely used materials in semiconductor strain gauges.

The study of TlIn$_{1-x}$Co$_x$Se$_2$ crystals in this regard led to very interesting results. First of all, it should be emphasized that crystals of solid solutions TlIn$_{1-x}$Co$_x$Se$_2$ show a strong piezoresistive effect in the [001] direction, which, in combination with their mechanical, elastic, crystallographic and a number of other features, makes them promising for creating new miniature highly sensitive and reliable electromechanical converters. as sensors of displacement, force, pressure, etc.

The efficiency of new TlIn$_{1-x}$Co$_x$Se$_2$ crystals in comparison with known crystals in semiconductor tensometry is provided mainly by the following three of their features, namely: - high (record) strain sensitivity (see tab. 1); high elasticity and tensile strength; the ability to easily cleave onto the desired identical fusiform rectangular plates with mirror edges in the direction of maximum piezoresistive effect [5-8].

Despite a number of common shortcomings of semiconductors for their practical application in strain gauges, due to their high strain sensitivity and small size, the number of developments of strain gauges based on various semiconductor materials is growing every day [9-13].

Table 1. *The average value of the strain-sensitivity coefficient (Ksr) of solid solutions TlIn$_{1-x}$Co$_x$Se$_2$ (0 ≤ x ≤ 0.5) in comparison with the initial TlInSe$_2$ crystals along the [001] axis.*

№	Load cell crystal composition	K$_{aver.}$, When compressed	K$_{aver.}$, When stretched	Note
1.	TlInSe$_2$	577	406	With relative deformation ε = 0,57·10^{-3} T = 300 K
2.	TlIn$_{0,99}$Co$_{0,01}$Se$_2$	2752	6641	
3.	TlIn$_{0,9}$Co$_{0,1}$Se$_2$	2839	6881	
4.	TlIn$_{0,5}$Co$_{0,5}$Se$_2$	2941	7143	

However, in terms of the magnitude of the strain sensitivity coefficient, the crystals of no known binary semiconductors are superior to silicon, although they have a number of distinctive features.

The highest strain sensitivity is currently found for crystals α - SiC p - type of conductivity (K = 470) [5]. Crystals TlIn$_{1-x}$Co$_x$Se in their sensitivity to deformation significantly exceed all materials known to date in semiconductor tensometry (Table 1).

The effect of temperature on the tensoresistive properties of TlIn$_{1-x}$Co$_x$Se$_2$ single crystals has been studied. The temperature dependence of the initial resistance and the change in the piezosensitivity coefficient with temperature are the most important indicators of semiconductor strain gauge materials. In the case of applying semiconductor strain gauges to a part with a variable temperature, it becomes necessary to take into account both changes. The change in the initial resistance of the sensor with temperature is taken into account by applying appropriate compensation methods, and the change in strain sensitivity is taken into account by introducing a correction. Nevertheless, the loss in sensitivity at elevated temperatures turned out to be inevitable: for the strain sensitivity of all materials known in semiconductor strain gauges decreases significantly with increasing temperature.

In this regard, the following valuable specificity of TlIn$_{1-x}$Co$_x$Se$_2$ crystals deserves special attention: with increasing temperature, the sensitivity to deformation increases significantly (Table 2). In this case, the strain gauge coefficient increases linearly with temperature. The strain sensitivity coefficient of TlIn$_{1-x}$Co$_x$Se$_2$ crystals of various compositions depending on temperature and relative deformation is given in Table 2.

The temperature coefficient of strain sensitivity per degree in percent, GT was determined by the formula: $G_T = \frac{\Delta K / K_0}{\Delta T} \cdot 100\%$, where ΔK is the change in the strain gauge factor when the temperature changes by ΔT, K$_0$ is the initial strain gauge factor at 300K, and the calculation results are shown in Table 3. The temperature coefficient of strain sensitivity of these crystals varied markedly from sample to sample, depending on its resistance - impurity concentration. The samples with the highest impurity concentration were characterized by the lowest value of the above temperature coefficients. The value of the latter significantly depended on the considered regions of the temperature interval.

Table 2. *Dependence of the strain sensitivity coefficient of solid solutions TlIn$_{1-x}$Co$_x$Se$_2$ on the composition and temperature [6].*

№	T, К	TlInSe$_2$	TlIn$_{0,99}$Co$_{0,01}$Se$_2$	TlIn$_{0,9}$Co$_{0,1}$Se$_2$	TlIn$_{0,5}$Co$_{0,5}$Se$_2$	Note
1.	300	577	1741	2839	2951	
2.	320	586	2442	3652	3460	With relative
3.	350	592	3170	4841	5011	deformation
4.	375	610	3930	5184	5928	ε = 0,57·10^{-3}
5.	410	655	4242	6088	7466	

Thus, strain gauges made of TlIn$_{1-x}$Co$_x$Se$_2$ crystals make it possible to provide high registration accuracy under temperature-controlled operating conditions. And in conditions of variable temperature, it is necessary to take into account the appropriate temperature corrections.

Table 3. *Temperature coefficient of strain sensitivity (G$_T$) of single crystals of solid solutions TlIn$_{1-x}$Co$_x$Se$_2$ on the composition.*

№	T$_{cp}$, К	TlInSe$_2$	TlIn$_{0,99}$Co$_{0,01}$Se$_2$	TlIn$_{0,9}$Co$_{0,1}$Se$_2$	TlIn$_{0,5}$Co$_{0,5}$Se$_2$	Note
1.	310	0,078	2,01	1,43	0,86	
2.	325	0,052	1,64	1,41	1,39	T$_{cp} = 20 + \frac{1}{2}\Delta T$
3.	337,5	0,034	1,67	1,10	1,34	
4.	355	0,052	1,31	1,04	1,39	

Another important feature of TlIn$_{1-x}$Co$_x$Se$_2$ crystals from the point of view of semiconductor tensometry was, as already noted, their significant flexibility (elasticity) and mechanical tensile strength; for example, TlIn$_{1-x}$Co$_x$Se$_2$ single crystals with dimensions of 0.25 x 1 x 10 mm withstand bending deformation with a curvature radius of up to 6 - 9 mm [5].

TlIn$_{1-x}$Co$_x$Se$_2$ crystals differ from all materials known in semiconductor tensometry by the advantage that the structural features of their crystal lattice provide splitting in the right direction into filamentous samples with mirror faces and the required geometric configuration.

4. Conclusion

In conclusion, it should be emphasized that the presence of a strong piezoresistive effect in TlIn$_{1-x}$Co$_x$Se$_2$ crystals allows

us to hope that highly sensitive displacement, force, and pressure sensors can be created on their basis. acceleration and torque sensors. It should also be noted that it is possible to significantly increase the sensitivity of sensors from single crystals of TlIn$_{1-x}$Co$_x$Se$_2$ solid solutions to measured values using temperature and optical illumination. The latter feature provides the simplest technology for manufacturing strain gauges; on their basis, a promising highly sensitive material appears for creating a modern strain gauge measuring transducer used to study the physical properties of materials, strains and stresses in parts and structures of the aviation and oil refining industries.

These strain gauges have a certain advantage compared to materials known in the literature:

1. small dimensions and weight;
2. short inertia, which allows the use of strain gauges for both static and dynamic measurements;
3. has a linear characteristic;
4. allow to carry out measurements remotely and at many points using the method of multipoint strain gauge;
5. the method of installing them on the parts and structures under study does not require complex devices and does not distort the deformation field of the part under study;
6. The work of strain gauges is based on the phenomenon of the piezophotoresistive effect, which consists in changing the active resistance of conductors when they are simultaneously exposed to mechanical deformation, temperature and optical illumination.;
7. The properties of these crystals remain stable with thousands of repetitions of the deformation and temperature test cycles at variable deformation (p = ±1.4·10^7 Pa) does not exceed 1.0 - 2.3% and they are more stable at critical temperatures and long-term loads compared to with strain gauges known in the literature, which indicates that single crystals of TlIn$_{1-x}$Co$_x$Se$_2$ solid solutions are promising materials for electronic technology.

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