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PIEZOELECTRIC PROPERTIES OF $TlIn_{1-x}Nd_xSe_2$ CRYSTALS

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The piezoelectric properties of $TlIn_{1-x}Nd_xSe_2$ *crystals* ($0 \le x \le 0.05$) *have been investigated. It has been found that these crystals possess high coefficients of tensosensitivity which change on partial substitution of the indium atoms by neodymiun atoms and strongly depend on the intensity of the spectral composition of optical illumination.*

In [1], using thermodifferential, microstructural, and x-ray phase analyses, it is established that in the $TlInSe_2$–$TlNdSe_2$ system the $TlInSe_2$-based solubility is observed in the region of 0–8 mol.% of $TlNdSe_2$. The electrophysical and thermal properties of these crystals are presented in [2, 3]. On the other hand, the investigation of the initial compound $TlInSe_2$ [4] has shown that it possesses a high tensosensitivity. The aim of the present work is to investigate the piezoelectric properties of the alloys in the $TlInSe_2$–$TlNdSe_2$ system with the use of an installation [5]. It should be emphasized that in the most general case a resistance strain gauge changes its cross section, length, and specific electrical resistance because of the action of the longitudinal mechanical stress, i.e., the total resistance depends on the geometric dimensions and the specific electrical resistance of the specimen.

The above-indicated factors can be represented in the form

$$R(\varepsilon) = \frac{\rho(\varepsilon)\, l(\varepsilon)}{S(\varepsilon)} . \tag{1}$$

Taking into account that $\rho(\varepsilon) = \rho_0(1 + \pi\varepsilon)$, $l(\varepsilon) = l_0(1 + \varepsilon)$, and $S(\varepsilon) = S_0(1 - \nu\varepsilon)^2$, we have

$$R = \frac{\rho_0 l_0 + l_0\, \rho_0 \pi\varepsilon + \rho_0 l_0 \varepsilon + \rho_0 l_0 \pi\varepsilon^2}{S_0 - 2S_0\nu\varepsilon + \varepsilon^2 S_0 \nu^2} . \tag{2}$$

Under small relative deformations $\varepsilon = \Delta l/l_0$, neglecting the terms with ε^2 and taking into account that the initial electrical resistance of the conductor is equal to $R_0 = l_0\rho_0/S_0$, we obtain

$$\frac{\Delta R}{R} = (1 + 2\mu + m)\,\varepsilon . \tag{3}$$

Thus, the coefficient of tensosensitivity is

$$K = 1 + 2\mu + m . \tag{4}$$

In contrast to metals for which the Poisson coefficient is approximately equal to 0.3, the quantity ΔR determined by the value of the coefficient m amounts in this case to only 20% ($K \sim 2$). In semiconductors, the quantity ΔR is virtually caused by the change in the specific electrical resistance ($K = m$). The investigations carried out have shown that $TlIn_{1-x}Nd_xSe_2$ crystals possess high coefficients of tensosensitivity, which, depending on the composition, can vary in the range 2000–30,000. It is found that $TlInSe_2$ crystals with dimensions 0.25 × 0.1 × 10 mm withstand bending with a radius of curvature of 4–7 mm, while the limit deformation amounts to 1.5%. We have determined the tensometric characteristics of the series of selected crystals as functions of the time and the deformation degree. Upon

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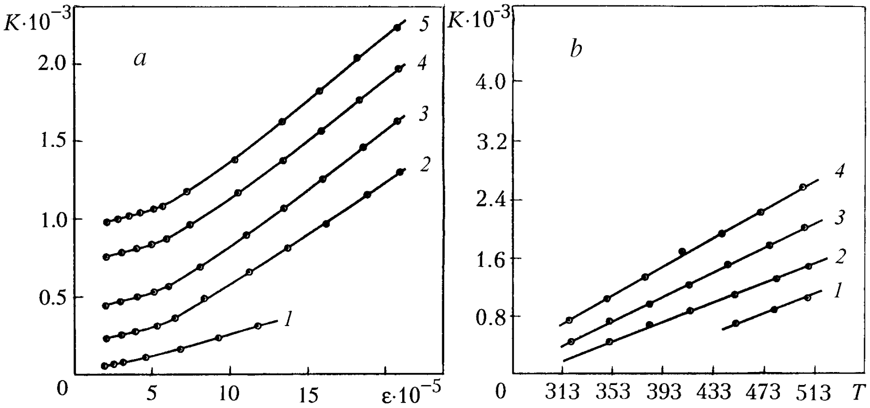

Fig. 1. Dependence of the tensosensitivity coefficient on the mechanical deformation of $TlInSe_2$ at different temperatures (a) [1) 300; 2) 400; 3) 450; 4) 500; 5) 550 K] and on the temperature at different values of the mechanical deformation (b) [1) $\varepsilon = 4 \cdot 10^{-5}$; 2) $10 \cdot 10^{-5}$; 3) $16 \cdot 10^{-5}$; 4) $22 \cdot 10^{-5}$].

applying the mechanical stress, we calculated the quantity $\beta = \Delta\rho/\rho$ of the $TlIn_{1-x}Nd_xSe_2$ crystals ($0 \le x \le 0.05$) in the following manner:

$$\beta = \Pi E\varepsilon = m\varepsilon .$$

Thus, the coefficient of tensosensitivity for semiconductors is determined first of all by the elastic constants of material in the corresponding crystallographic directions and it is directly proportional to the Young modulus E [2].

According to the results of preliminary measurements, the quantity E in the crystallographic direction [001] in the $TlIn_{1-x}Nd_xSe_2$ single crystals (at 300 K) changes within the limits $E = (13.5\text{–}161.3) \cdot 10^{10}$ N/m^2 depending on their composition, which considerably exceeds the corresponding quantities for materials existing at present in semiconductor strain metering. However, in our opinion, the chief reason for the strong piezoresistance effect observed in $TlIn_{1-x}Nd_xSe_2$ crystals is mainly the fact that they have a complex energy structure.

From the interpretation of the band structure of $TlInSe_2$ carried out by pseudopotential methods it is found that the valence-band top is located at point D (0.5, –0.5, 0.5) on the Brillouin-zone boundary, while the conduction-band bottom is located at point F (0.5, 0.5, 0). Thus, the results obtained have shown that the compound $TlInSe_2$ is a direct-band-gap semiconductor. According to selection rules, the smallest direct transition is forbidden.

The valence bands can conventionally be separated into three groups:

1) four bands formed by the *s*-states of selenium atoms are located near the level of 12 eV;

2) a weakly isolated group of four bands, which are formed mainly by the *s*-states of thallium and indium atoms, is observed in the region 5–6 eV;

3) the remaining ten bands are located in the region 0–4 eV and result in the main from the *p*-states of the selenium, thallium, and indium atoms.

To verify the dependence of the piezoresistance effect on the angle of rotation of the bending plane, the investigated crystals with contacts were vertically glued onto the indicator axis. A magnetic tip was glued to the upper crystal face, while the bending of the crystal was carried out using an electromagnet (of the RP-7 type) installed in the transverse direction. The value of the deflection of the free tip in all directions was kept constant ($\Delta x = 0.3$ mm) and was monitored by the sight lines of an MBS-1 microscope. The indicator arrow read the angle of rotation of the bending plane φ. Here, the piezoresistance effect was observed in none of the directions of free bending. A perceptible change in the resistance of the $TlInSe_2$ crystal was revealed at angles of torsion from 60 to 90°. In the given region, the change turned out to be linear with a proportionality coefficient of $\alpha = 4 \cdot 10^{6}$ Ω/K ($R_0 = 690$ MΩ). The angle $\varphi = 102^{\circ}$ was the limit of torsion. It should be emphasized that in this case the maximum effect was observed on stretching the $TlInSe_2$ crystals along the crystallographic axis [001].

The investigations carried out have shown that the sensitivity of $TlIn_{1-x}Nd_xSe_2$ can be increased by increasing the temperature and in the presence of optical illumination. In particular, we found that the dependence of the ten-

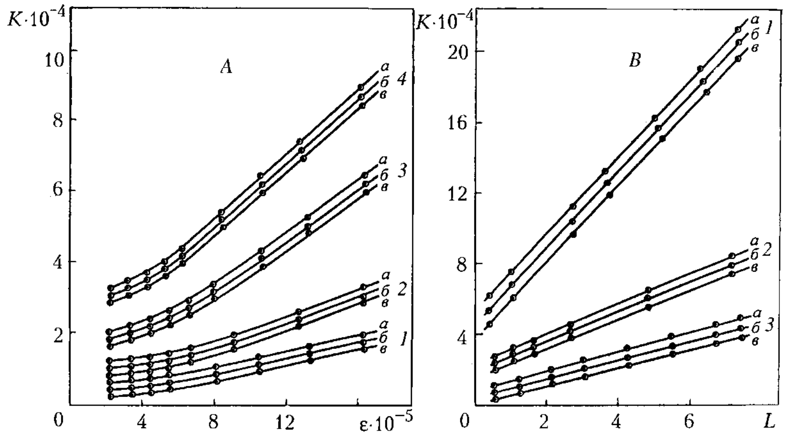

Fig. 2. Dependence of the tensosensitivity coefficient of the TlIn$_{1-x}$Nd$_x$Se$_2$ crystals [a) $x = 0$, b) 0.04, and c) 0.08] on the mechanical deformation at different values of the optical illumination (A) [1) 0; 2) 1000; 3) 10,000; 4) 43,000 lx] and on the optical illumination at different values of the mechanical deformation (B) [1) $\varepsilon = 1\cdot10^{-5}$; 2) $10\cdot10^{-5}$; 3) $22\cdot10^{-5}$].

sosensitivity of the investigated crystals on the temperature increases linearly (Fig. 1); the relative change in g_T per unit degree in percentage amounts to

$$g_T = \frac{\Delta K}{K\Delta T}\cdot 100\% = (0.13 - 0.15)\%/\mathrm{K}\,.$$

Resistance strain gauges based on TlInSe$_2$ make it possible to ensure the high accuracy of recording under thermostatted operating conditions, whereas under the conditions of a variable temperature to do this requires account for the corresponding temperature corrections. As thermal resistors, it is also convenient to use TlIn$_{1-x}$Nd$_x$Se$_2$ crystals.

In investigating the tensometric features of the TlIn$_{1-x}$Nd$_x$Se$_2$ crystals, we revealed a new effect, which involves a tensosensitivity change in the presence of optical illumination. This effect is piezophotoresistive and its magnitude considerably depends on the intensity of the spectral composition of the optical illumination. From the results of investigation of the coefficient of tensosensitivity of the TlIn$_{1-x}$Nd$_x$Se$_2$ crystals as a function of the mechanical deformation and the optical illumination in the static regime (Fig. 2), it is evident that the relative change in the tensosensitivity coefficient $\Delta K/K$ per unit light intensity irrespective of the deformation degree has the same order: under the deformation $\varepsilon = 2.2\cdot10^{-4}$ we have the constant $g_L = \frac{\Delta K}{K\Delta L}\cdot100\% = 2\cdot10^{-3}$ %/lx, while for $\varepsilon = 1\cdot10^{-5}$ the quantity g_L is equal to $\frac{\Delta K}{K\Delta L}\cdot100\% = 1.7\cdot10^{-3}$ %/lx.

The piezophotoresistance effect is manifested more clearly on irradiation of TlInSe$_2$, TlIn$_{0.99}$Nd$_{0.01}$Se$_2$, and TlIn$_{0.98}$Nd$_{0.02}$Se$_2$ crystals which undergo deformation in the dynamic regime. It should be noted that increasing the tensosensitivity of the TlIn$_{1-x}$Nd$_x$Se$_2$ crystals by optical and thermal methods will allow one to substantially extend the capabilities of semiconductor tensometry.

Thus, carrying out investigations of the influence of the mechanical deformation and the electromagnetic radiation on the electrophysical properties of TlIn$_{1-x}$Nd$_x$Se$_2$ crystals, we have established a substantial change in the tensosensitivity coefficient of these crystals.

NOTATION

$\varepsilon = \Delta l/l$, relative mechanical deformation; R, total resistance, Ω; l, specimen length, m; S, cross section of the specimen, mm^2; ρ, specific resistance, Ω·m; μ, Poisson coefficient; m and ν, dimensionless proportionality coefficients;

K, tensosensitivity coefficient; Π, proportionality coefficient between the change in the specific resistance and the deformation; E, Young modulus, N/m^2; T, temperature, K; g_T and g_L, relative changes in the tensosensitivity coefficient per unit degree and per unit light intensity, %/K and %/lx; x, deflections of the free specimen end, mm; φ, angle of torsion, deg; D, valence-band top, eV; F, conduction-band bottom, eV; L, optical-illumination intensity, lx; $\beta = \Delta\rho/\rho$, relative change in the specific electrical resistance; $\alpha = \Delta R/T$, change in the total resistance of the specimen per unit degree, Ω/K. Subscripts: 0, absence of mechanical deformation.

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