ON THE CHARGE TRANSFER IN LAYERED SEMICONDUCTOR INDIUM SELENIDE

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At a variety of external and intracrystalline conditions experimentally studied electrical parameters and characteristics in the layered indium selenide semiconductor. A discussion of the results is made and the physical mechanism of found specific characteristics has been explained.

Keywords: crystal, doping, conductivity, a rare earth element, mobility of free charge carriers, Hall constant, drift barrier.
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1. INTRODUCTION

Often progress in fundamental and applied physics is determined by developments in the receipt and study of new semiconductor materials. As revealed at that theoretically unpredictable physical effects not only stimulate the development of the theory of semiconductors, but also the creation of fundamentally new functional elements for a variety of electronics industries.

Therefore, physicists and technologists continually conducted an intensive search in direction to prepare new semiconductor materials with specific structural features and a comprehensive study of varieties of their physical properties.

One of these materials is also indium monoselenide (InSe) belonging to the class of semiconductor compounds $A^{III}B^{VI}$ [1]. The peculiar (layered) crystal structure of this semiconductor gives it unique physical properties that for many years attracts attention of a wide circle of researchers various specialties.

To date the experimental study of the physical properties of InSe was the subject of many studies [-4], and in some cases has been found "unusual" features, i.e. they are not explained in the framework of theoretical ideas about physical properties of quasi-homogeneous crystalline semiconductors [5] and need for additional studies.

In the present paper we report about some of these "unusual" characteristics of the charge transport phenomena in *n*-InSe single crystals, received by us from comprehensive experimental studies of the effect of various external impacts and intracrystalline factors (doping, spatial heterogeneity, etc.) on their electrical parameters and characteristics. Naturally, such experimental studies, in addition to revealing the new features of this semiconductor, may also be useful to clarify the mechanism of various electronic effects also in other partially disordered crystalline semiconductors and identify new opportunities for their practical applications.

2. EXPERIMENTAL PROCEDURE AND SAMPLES

The investigated samples in the form of a rectangular parallelepiped with a thickness along the axis "C" (~ 300 μm) and lateral dimensions over the plane "C" (~ 2÷3x6÷8 mm) of the crystal cleaved from different portions of the same or different single crystalline ingots grown by slow cooling at constant gradient along the alloy [6]. Measurements were carried out in a wide range of temperatures (77- 450 K), intensity (E) of the external electric field (from extremely weak up to the switch voltage [4]). Pure and doped with rare earth elements (REE) samples were taken. As an impurity dysprosium, holmium and gadolinium were used. The doping was performed by introducing a desired quantity of the dopant in powder form into a batch before the synthesis process.

3. EXPERIMENTAL RESULTS

Studying the temperature dependence of the electrophysical parameters - specific conductivity (σ), the Hall constant (R_H) and the mobility of free charge carriers (μ) in *n*-InSe crystals it is found that in the temperature region below room temperature, conductivity (σ) of different samples differ depending on their technological origin. With decreasing temperature (T) from room temperature to liquid nitrogen temperature, R_H value is almost unchanged and has approximately the same numerical value for the different samples. In the crystals in which the value of σ at 77 K (initial specific conductivity value) not more than $10^{-4}\Omega^{1}\cdot cm^{-1}$, temperature dependence of σ and μ, unlike R_H, exhibit activation character, i.e. σ, $\mu \sim -\frac{\Delta\varepsilon}{kT}$ (fig. 1), where $\Delta\varepsilon$ - activation energy, k - Boltzmann constant.

The latter suggests that the observed at the low temperature region $\sigma(T)$ relationship in such (high resistance) crystals is not due to the temperature dependence of the concentration, and is associated with the dependence of the mobility of free charge carriers on the temperature.

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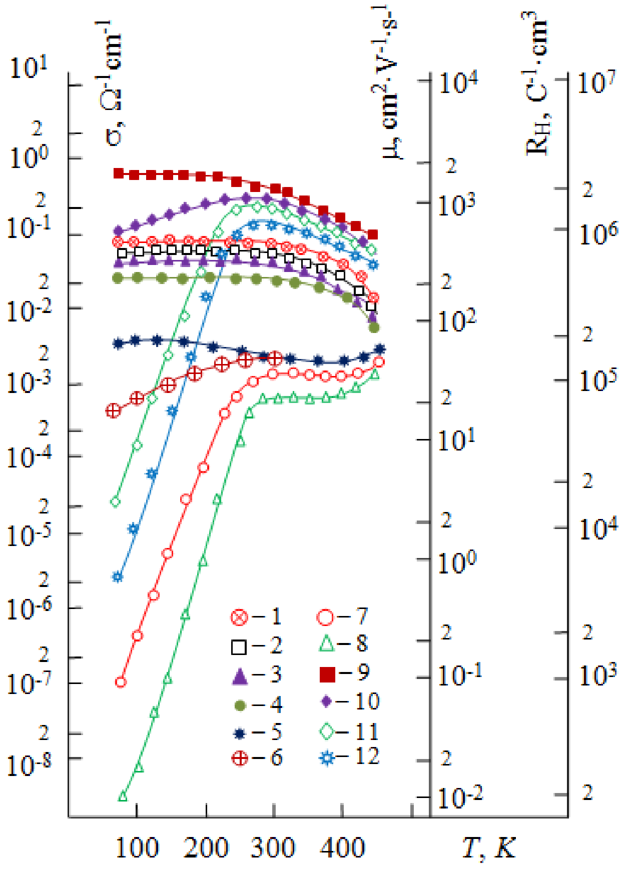

Fig.1. The temperature dependence of the Hall coefficient (R_H) (kr. 1-4), electrical conductivity (σ) (curves 5-8), and the mobility of free charge carriers (μ) (curves 9-12) in n-InSe crystals with different initial specific conductivity (σ_0): σ_0, $\Omega^{-1}\cdot$cm^{-1}: 1, 3, 5 - $2\cdot10^{-3}$; 2, 4, 6 - $2\cdot10^{-4}$; 7, 8, 9 - $2\cdot10^{-5}$; 10, 11, 12 - $6\cdot10^{-6}$.

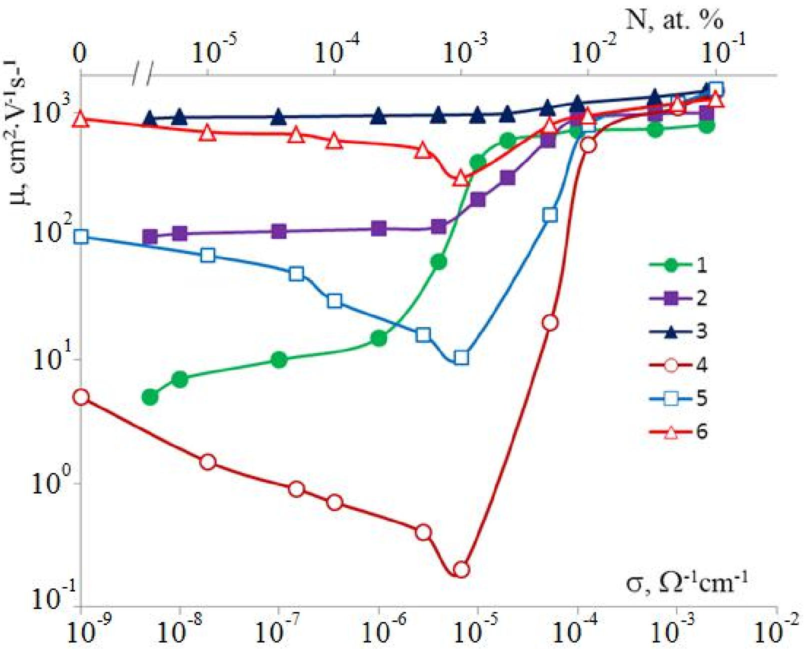

Fig.2. The dependence of the mobility of free charge carriers (μ) on the initial value of conductivity (σ_0) (curves 1-3) and the content of the introduced impurity (N) REE (curves 4-6) at different temperatures.
T, K: 1, 4 - 77; 2, 5 - 200; 3, 6 - 300.

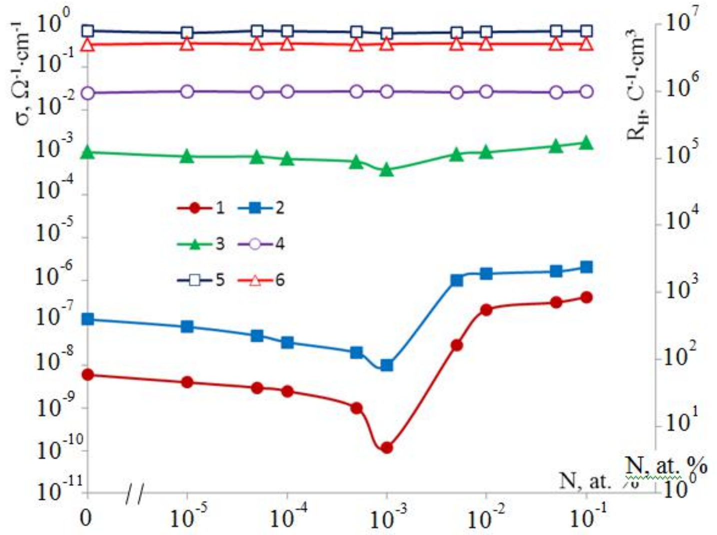

Fig.3. The dependence of the Hall coefficient (curves 1 to 3) and electrical conductivity (σ) (curves 4- 6) on the content of the introduced REE impurity (N) at different temperatures.
T, K: 1, 4 -77; 2, 5 - 200; 3, 6 - 300.

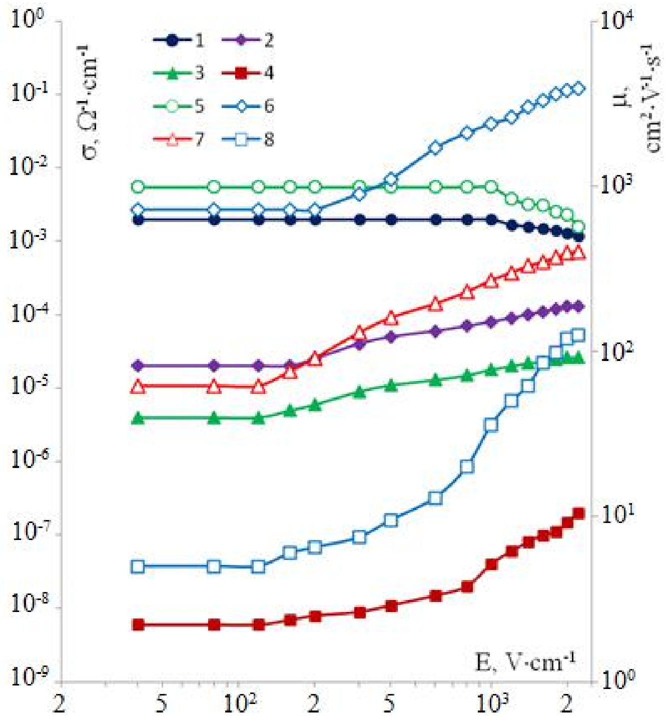

Fig.4. The dependence of specific conductivity (σ) (curves 1- 4) and mobility of free charge carriers (curves 5-8) on the electric field intensity (E) in pure (a) and doped with rare-earth elements (b) n-InSe crystals at 77 K.
a) σ_0, $\Omega^{-1}\cdot cm^{-1}$: 1, 5 – $2\cdot10^{-3}$; 2, 6 - $2\cdot10^{-5}$; 3, 7 - $4\cdot10^{-6}$; 4, 8 - $6\cdot10^{-7}$;
b) N, at. %: 1, 5 - 0; 2, 6 - 10^{-5}; 3, 7 - 10^{-3}; 4, 8 - 10^{-1}.

However, the experimentally observed dependence of $\mu(T)$ is not subject to the theoretical concepts of mobility of free charge carriers in quasi-ordered crystalline semiconductors [5].

At low temperature region were also found not characteristic for quasi-ordered crystalline semiconductors peculiarities for dependence of electrophysical parameters on doping (fig. 2 and 3) of the test specimen and on the impact of the external electric field (fig. 4). In particular, it was found that the value of μ in darkness at 77 K in low-resistivity crystals amounts up $1000\div1500 cm^2/V\cdot s$ and with decreasing σ to $5\cdot10^{-7}\Omega^{-1}\cdot cm$ decreases to parts per units.

In contrast to the low temperature region, at high temperatures $\mu(T)$ relationship obeys the law, which is characteristic for the mobility of free charge carriers in a quasi-ordered crystalline semiconductors with the dominance of the scattering of free charge carriers on acoustic lattice vibrations, i.e. $\mu\sim T^{-\frac{3}{2}}$ relationship is observed (fig. 1). When other conditions being equal, with increase in the initial value of conductivity (σ_0) course of $\mu(T)$ curves approaches to predict by the theory for mobility of free charge carriers in quasi-ordered crystalline semiconductors. Effect of doping with rare earth elements on σ is observed only at low temperatures and at low doping levels (N<10^{-2}at.%). And it manifests itself both in changes of absolute value of μ and σ, and in the course of curves of dependences of these quantities on various external factors with *N* (fig. 2 and 3). It turned out that under considered by us conditions in the studied semiconductor values and characteristics of the electrophysical parameters are independent of the chemical nature of the introduced rare-earth impurity.

The specificity of the dependence of the charge transport from the influence of the external electric field (fig. 4) in *n*-InSe crystals is what, at that marked $\sigma(E)$ dependence starts to occur at relatively low values of *E* and has a very different character than predicted by corresponding theory for the dependence of the kinetic phenomena on *E* in the case of heating of free charge carriers in semiconductors by electric field [7].

4. DISCUSSION

We assume that found in high-pure and lightly doped with REE n-InSe crystals at measurements carried out by us specific (not explained in terms of theoretical concepts of the charge transport phenomena in quasi-ordered crystalline semiconductors) features of the charge transport is primarily associated with the presence in free bands of the semiconductor the drift and recombination barriers, with the original (taking place at 77 K) energy height for different samples ~ (0.05÷0.20) eV and ~(0.15÷0.40)eV. In favor of the validity of this assumption also testifies experimentally observed temperature dependence of the current density in these samples [3]. Detected at that dependence is associated with electrical erasing the drift barriers due to the implementation of a significant injection.

As for the whence of these barriers, first of all they can be caused by layered crystal structure of the semiconductor, segregation of its component atoms along the ingot during growth, as well as because of the variety of modifications [1].

5. CONCLUSIONS

The experimental results and their discussions lead to the following conclusions:

- When otherwise identical conditions the conductivity of individual samples of the layered n-InSe semiconductor single crystals in the low temperature region (T < 300 K) depends on technological origin of the examined sample;
- In high-resistivity ($\sigma_0 \leq 10^{-5} \Omega^{-1} \cdot cm^{-1}$) crystals charge transport has specific (not explained by the theory of charge transport in a quasi-ordered crystalline semiconductors) features;
- These specific features of the charge transport in studied semiconductors directly related to the presence of the drift and recombination barriers in free bands of high-resistance crystals, as well as to control their parameters in different ways (temperature, doping, injection).

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