Effect of random macroscopic defects on kinetic phenomena in a layered semiconductor n-InSe with strong electric fields

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Abstract. In single-crystal n-InSe layered semiconductors at 77÷300 K, the dependence of the electrical conductivity on the strength of a strong electric field by an ultrahigh frequency (UHF) was studied. It was established that at low temperatures, the magnitude and course of the change in conductivity under the action of a strong electric field in samples with different initial (existing at 77 K) specific conductivities differ. The dependence of the electrical conductivity on the electric field strength in the most low-resistance samples is satisfactorily described by the theory of heating of charge carriers by the electric field in spatially homogeneous crystalline semiconductors, and with a decrease in the value of specific conductivity, it disagrees with this theory. It is shown that these discrepancies are due to the presence of random macroscopic defects in the crystals under study, which are formed due to the weakness of the interlayer coupling.

1. Introduction
To date, the kinetic properties of semiconductors in strong electric fields have been studied in many papers [1, 2]. However, the features and mechanism of the dependence of electrical conductivity on the electric field in semiconductors with random macroscopic defects [3] are not well understood.

In the present work, in order to identify the features and mechanism of heating of charge carriers by the electric field in semiconductors with random macroscopic defects, the dependences of conductivity on the action of a strong electric field by an ultra-high frequency (UHF) in n-InSe single crystals are investigated. Based on this, in the present work, the dependence of conductivity on the electric field strength in single crystals of layered n-InSe semiconductor was investigated.

2. Materials and methods
To eliminate the influence of contact phenomena, electrical breakdown, Joule heating of the crystal lattice on the interaction of charge carriers with point and macroscopic defects, measurements were performed when the sample under study rarely repeated, short-term electric field pulses with ultra-high frequency (UHF) with smoothly controlled - by the intensity from zero up to ~ 10⁷ V/cm at various temperature - temperature (in the range of 77÷300 K).

The investigated samples were cut from different parts of the large single-crystal n-InSe ingot grown modified by the Bridgman method. On the basis of complex structural analyzes, it was
established that the obtained ingots are single-phase, have a single-crystalline structure, and belong to the space group $R3m$ ($C_{6v}$) with cell periods $a \approx 4.003\,\text{Å}$, $c \approx 24.955\,\text{Å}$ [4]. The phases of substitution of selenides of other chemical elements, oxides and free precipitates of the constituent components of InSe, and the presence of other modifications were not detected in them.

The current contacts from metallic indium are located so that, when measured, the electric vector of the microwave field and the current generated by a constant voltage applied to the sample are directed along the natural layers of the crystal.

For a sufficiently reliable explanation of the results obtained, the Hall coefficient ($R_X$), specific conductivity ($\sigma$) and Hall mobility of charge carriers ($\mu$) in $n$-InSe crystals with different initial values of conductivity $\sigma_0$ (at 77 K), $\sigma_0$, $\Omega^{-1}\cdot\text{cm}^1$; curves (1, 2, 4) - $3.3\cdot10^{-4}$; curves (3, 5, 6) - $8\cdot10^{-7}$

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3. Results and discussion

It was established that at $T \leq 300$ K, in contrast to $R_x$, the values of $\mu$ and $\sigma$, for different samples, are markedly different (Figure 1). At 77 K, the highest value of $\mu$ is observed in the samples with the highest initial conductivity (available at 77 K) conductivity ($\sigma_0$) and with a rise in temperature to 300 K it slightly increases. The identical course has also the curves of $\sigma(T)$, and $R_x$ does not depend on
temperature. In the crystals under study, with decreasing \( \sigma_0 \), the magnitude of \( \mu_x \) monotonously decreases, and the value of \( R_x \) does not change (Figure 2). With an increase in temperature from 77 K, the values of \( \sigma \) and \( \mu_x \) increase, gradually approaching the corresponding values of \( \sigma \) and \( \mu_x \), which occur in samples with the largest \( \sigma_0 \). At \( T \approx 300 \) K, the values of \( \sigma \) and \( \mu_x \) for samples with different \( \sigma_0 \) do not differ. In the temperature range \( T \approx (77 \div 300) \) K, the dependences \( \sigma \), \( \mu_x \) (\( T \)) have an activation character with the same activation energy for \( \sigma \) and \( \mu_x \) (\( \Delta \varepsilon_{\mu} \approx \Delta \varepsilon_{\sigma} \)). When exposed to a microwave electric field with a voltage (\( E \)) greater than a certain critical (\( E_{cr} \)), the conductivity value of the studied n-InSe crystals changes (Figure 3). Moreover, as the value of the relative change in conductivity (\( \frac{\Delta \sigma}{\sigma_L} \), where \( \Delta \sigma = |\sigma_L - \sigma_s| \), \( \sigma_L \) and \( \sigma_s \) are the values of the specific conductivity of the sample under study at electric fields with \( E < E_{cr} \) and \( E \geq E_{cr} \), respectively), and the course of its dependence on \( E \), in addition to temperature, also depends on the value of \( \sigma_0 \).

![Figure 2](image-url)

**Figure 2.** Dependence of the Hall mobility of charge carriers (curve 1) and the Hall coefficient (curve 2) on the initial resistivity of n-InSe crystals.

The value of \( E_{cr} \) observed in the experiment also turns out to be dependent on the magnitude of \( \sigma_0 \) and differs from the theoretically calculated number (\( E_{cr}^T \)). With a decrease in \( \sigma_0 \), the value of \( E_{cr} \) increases both in its absolute value and relative to \( E_{cr}^T \). With an increase in the sample temperature to 300 K and with an increase in the value of \( \sigma_0 \) to its maximum value, these differences gradually diminish.

The experimentally found dependence \( \sigma(E) \) in samples with the largest value \( \sigma_0 \) satisfactorily obeys the theory of kinetic phenomena in spatially homogeneous crystalline semiconductors under strong electric fields, where, due to the heating of charge carriers by an electric field, conductivity decreases, the dependence \( \sigma(E) \) obeys the power law, and the exponent depending on the value of \( E \) and \( T \) is -2.0, -1.0, -0.5. In higher resistance crystals at low temperatures, a significant deviation of the experimental results from the above theory is observed. In particular, up to a certain value of \( E \), their conductivity...
sharply increases with respect to $\sigma_L$, and then decreases according to a law that is identical for the lowest resistance crystals. With an increase in $\sigma_0$ and with an increase in $T$, this deviation gradually weakens, finally in all investigated crystals at $T\approx300$ K, and in samples with the largest value $\sigma_0$ at $T\geq180\div200$ K disappears.

Figure 3. Dependence $\frac{\Delta \sigma}{\sigma_0}$ on the electric field strength at different temperatures in n-InSe single crystals with different values of $\sigma_0$.

$\sigma_0, \Omega^{−1}\cdot\text{cm}^{−1}$; curves (1, 3, 5) – $3.3\cdot10^4$; curves (2, 4, 6) – $8\cdot10^7$; $T$, K: curves (1, 2) – 77; curves (3, 4) – 160; curves (5, 6) – 300

An analysis of the experimental results obtained allows us to conclude that the effects of a strong electric field on the conductivity of single crystals of layered semiconductor n-InSe, which were found at $T\leq300$ K compared to those occurring in spatially homogeneous crystalline semiconductors of anomaly, are primarily due to with the presence of random macroscopic defects in them, which create drift and recombination barriers in the free energy zones of this semiconductor. In particular, due to the weak (molecular) coupling between adjacent layers of single crystals, samples of this semiconductor have the same chemical composition and crystal structure with the main matrix, but noticeably low conductivity compared to it random macroscopic defects (RMD) [6]. Therefore, samples of n-InSe single crystals as a whole consist of a low-impedance matrix with random high-resistance macroscopic defects (inclusions) and have local levels of various types [2] in the band gap. Due to the presence of the RMD in the samples under study, in addition to the recombination samples, drift barriers that determine the behavior of the conduction transfer also appear. In such a double-
barrier crystalline semiconductor, the change in conductivity under the action of a strong electric occurs both due to a change in concentration and due to a change in the mobility of charge carriers. Unlike high-resistance, the most low-resistance n-InSe crystals in potential reliefs of free energy zones are close to spatially homogeneous crystalline semiconductors and their kinetic properties are satisfactorily described based on the concepts of the theory of spatially homogeneous crystalline semiconductor with different local levels in the forbidden zone.

Due to the obstacle of drift barriers on the movement of charge carriers, the concentration and mobility of carriers ($<n>$ and $\mu_{dr}$, respectively) participating in conductivity differs from those determined by Hall measurements ($n_x$ and $\mu_x$, respectively) and there is a relationship between them [7]:

$$\mu_x = \frac{\mu_{dr} <n>}{n_x}.$$  

At $T \leq 300 K$ in samples with the smallest $\sigma_0$ value, the values of $<n>\omega n_s$, $\mu_c\omega\mu_{dr}$, but the value of $\mu_{dr}$ is sufficient to carry out the heating of carriers by an electric field at $E \geq E_{cr}$.

For this reason, when $E \geq E_{cr}$ with increasing $E$, the effective temperature of charge carriers ($T_e$) rises with a concentration of $<n>$. Further, due to the transfer of a certain part, the additional energy acquired by them to carriers with lower mobility and, similarly to the case of an increase in the temperature of the crystal lattice, the value of $<n>$ approaches $n_x$. As a result, the electrical properties of the studied high-resistance crystals in stronger electric fields approach those that occur in the lowest-resistance (spatially homogeneous) crystals.

4. Conclusion
In contrast to spatially homogeneous crystalline semiconductors, to which n-InSe crystals with the largest $\sigma_0$ are closer, in higher-resistance crystals, where the value of $\mu_x$ is significantly small due to the presence of drift barriers, the electron gas is heated by an electric field due to the high $\mu_{dr}$ value participating in the conduction of charge carriers with a concentration of $<n>$.

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