Photo-e.m.f. at a metal/layered n-InSe semiconductor contact under heating conditions of current carriers by an electric field

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Abstract. The features of the photo-e.m.f. are experimentally studied on the metal/n-InSe contact under conditions of heating the current carriers by an electric field in the temperature range of T=77÷350 K. The dependences of the photo-e.m.f. (U\textsubscript{ph}) value have been measured in the absence of (U\textsubscript{ph}\textsuperscript{0}) and under the condition of heating the current carriers (U\textsubscript{ph}\textsuperscript{f}), as well as the value of ΔU\textsubscript{ph}=U\textsubscript{ph}\textsuperscript{f}-U\textsubscript{ph}\textsuperscript{0} from the wavelength (λ) and light intensity (I), heating electric field strength (E), time (τ), temperature (T\textsubscript{0}), the initial value of the dark resistivity (ρ\textsubscript{D0}) at 77K n-InSe. It has been established that the heating of current carriers by an electric field significantly affects the magnitude and behavior of the photo-e.m.f. characteristics on the metal/n-InSe contact. The nature of this effect depends on T\textsubscript{0}, ρ\textsubscript{D0}, I. The value of U\textsubscript{ph}\textsuperscript{f} significantly exceeds the value of U\textsubscript{ph}\textsuperscript{0}. With an increase in E, the value of ΔU\textsubscript{ph} increases linearly (ΔU\textsubscript{ph}~E) at relatively small E, and the dependence of ΔU\textsubscript{ph}(E) reaches saturation at higher E. The value of ΔU\textsubscript{ph} decreases with increasing ρ\textsubscript{D0}, at relatively small E. With an increase in ρ\textsubscript{D0}, the relaxation time of the photo-e.m.f. also increases when turned off the pulse of the electric field. The obtained experimental results are explained on the basis of the dependence of the photo-e.m.f. on the metal/n-InSe contact on the effective temperature of heated current carriers (T\textsubscript{e}), considering the effect of the spatial inhomogeneity of n-InSe crystals on the photo-e.m.f. and on the process of heating the current carriers.

1. Introduction

The study of various types of photovoltaic effects in semiconductors [1, 2] is of interest both for studying the mechanism of generation-recombination processes, the interaction of free charge carriers with various defects in semiconductor materials and contact structures, as well as for creating photoelectric light receivers and converters of light energy, including solar, electric.

Moreover, it is known that the study of the effect of the strong electric field on various, in particular, photoelectric properties in semiconductors creates a unique opportunity to study their structure and physical properties [3-6]. In early works [7, 8], we reported on the experimental results obtained in the study of the dependence of electrical conductivity on the electric field strength [7] and thermoelectric...
power. hot current carriers [8], caused by the heating of current carriers by an electric field, in single crystals, which are one of the characteristic representatives of the class of A_{III}B_{VI} semiconductor compounds with a layered n-InSe structure. In this work, we are investigated the features of the photo-e.m.f. at the metal/n-InSe contact under conditions of heating the current carriers by an electric field. Indium selenide has been investigated due to the high mobility of free charge carriers in this semiconductor [7, 8], which is necessary for their heating by an electric field and to study the effects of hot carriers.

2. Materials and methods
The measurements were carried out in the temperature range of $T_0=77\div350$ K at the valve mode. The heating of the current carriers was carried out by exposing the structures of the sample to rarely repeated (with a repetition rate of no more than 6-7 Hz), short (with a duration $\tau_{UHF}=2.5$ μs) pulses of a microwave electric field ($10^{10}$ Hz) with an intensity of $\tilde{E}=2\cdot10^2\div5\cdot10^3$ V/cm [7, 8]. Metallic indium, tin, or silver paste were used as contact materials. The contacts were located so that in all measurements the incident light flux on the structure under study was directed perpendicular to the (001) plane of the crystal, and the photo-e.m.f. and heating microwave electric field strengths, along natural layers - (001) plane of the crystal [9]. During the measurements, the illuminated contact was in the zone of action, and the second (unlit) contact was outside the zone of action, which heats the carriers of the microwave electric field. The samples were cleaved from single-crystal n-InSe ingots grown by the Bridgman method. The value of the initial (having at a temperature of 77 K) dark resistivity of the n-InSe component of various samples was different and amounted to $\rho_{D0}=2\cdot10^3\div4\cdot10^6$ Ω·cm. With an increase in $T_0$, the difference between the values of the dark resistivity of different samples decreased and at $T_0\geq250$ K completely disappeared.

3. Results and discussion
The photo-e.m.f. dependences on the wavelength and intensity of the light incident on the sample, the value of $T_0$, the value of $\rho_{D0}$, the intensity of the microwave electric field heating the current carriers and the time under different conditions were studied for metal/n-InSe contact.

![Figure 1](image)

**Figure 1.** Dependence of $\Delta U_{ph}$ on the electric field strength at different values of the initial dark n-InSe resistivity at the metal/n-InSe contact.

$T_0=77$ K; $\lambda=0.95$ μm; $I=0.25\cdot I_0$;
$\rho_{D0}$, Ω·cm: 1 - 2·10^3; 2 - 6·10^3; 3 - 8·10^3; 4 - 4·10^6
Figure 2. Dependences of $\Delta U_{\text{ph}}$ on the value of the initial dark resistivity of n-InSe (curves 1 and 2) and light intensity (curves 3 and 4) in the metal/n-InSe contact. $T_0=77$ K; $\lambda=0.95$ $\mu$m; $I/I_{\text{max}}$: 1, 2 - 0.25; $E$ (V cm$^{-1}$): 1 - 5·10$^3$; 2, 3, 4 - 6·10$^3$; $\rho_{D0}$, $\Omega$·cm: 3 - 2·10$^3$; 4 - 4·10$^6$.

It was found that the heating of current carriers by an electric field significantly affects the magnitude and behavior of the main characteristics of the photo-e.m.f. in the metal/n-InSe contact. Moreover, the nature of this effect, in turn, depends on $T_0$, $\rho_{D0}$, wavelength ($\lambda$) and intensity ($I$) of the light incident on the investigated contact.

In all the samples, the $U_{\text{ph}}$ value significantly exceeds the $U_{\text{ph}}^0$ value. In samples with the lowest initial dark resistivity ($\rho_{D0} \approx 2\cdot10^4$ $\Omega$·cm), the dependence $\Delta U_{\text{ph}}(E)$ first (at relatively small $E$) has a quadratic character ($\Delta U_{\text{ph}} \sim E^2$), then (at higher $E$) it becomes linear ($\Delta U_{\text{ph}} \sim E$) and gradually reaches saturation (Figure 1, curve 1). In weakly heating electric fields, the value of $\Delta U_{\text{ph}}$ decreases with increasing the value of $\rho_{D0}$ (Figure 2, curve 1), and the course of the dependence $\Delta U_{\text{ph}}(E)$ becomes sharper than the quadratic one. In samples with $\rho_{D0} \approx 4\cdot10^6$ $\Omega$·cm, the exponent of the dependence $\Delta U_{\text{ph}}(E)$ in the region of weakly heating electric fields reaches $\sim 4$ (Figure 1, curves 2-4).

The dependence $\Delta U_{\text{ph}}(I)$ has a linear character at not very high light intensities, and then, gradually reaches saturation with an increase in $I$ (Figure 2, curves 3 and 4). The spectral distribution of $\Delta U_{\text{ph}}$ correlates well with the spectral distribution of intrinsic photoconductivity in n-InSe single crystals [10] - it covers the wavelength range of the optical spectrum $\lambda=0.35$÷1.25 $\mu$m and has a maximum at $\lambda=0.95$ $\mu$m.

The value of $\Delta U_{\text{ph}}$ in samples with $\rho_{D0} < 10^4$ $\Omega$·cm decreases with increasing $T$, and in samples with $\rho_{D0} > 3\cdot10^5$ $\Omega$·cm - it increases and reaches the values that occur in samples with the lowest resistance n-InSe crystals. The difference between the values and paths of the dependences $\Delta U_{\text{ph}}$ for samples with n-
InSe crystals with different \( \rho_{D0} \) also disappear at high values of the electric field heating the current carriers (Figure 2, curve 2) and the intensity of the light incident on the sample (Figure 2, curves 3 and 4).

The relaxation rate \( \Delta U_{ph} \) after the termination of the action of the strong electric field heating the current carriers also depends on the value of \( \rho_{D0} \) and decreases with an increase in the latter - the process becomes slowly relaxing. In this case, the relaxation time \( \Delta U_{ph} \) increases with increasing the value of \( \rho_{D0} \) (Figure 3).

Obtained experimental results are explained on the basis of the dependence of the photo-e.m.f. on the metal/semiconductor contact on the effective temperature of current carriers \( (T_e) \), taking into account the influence of the spatial inhomogeneity of n-InSe crystals, on the process of heating the current carriers by an electric field. It is assumed that under the considered conditions at constant \( T_0 \), in particular, in the region of low \( T_0 \), included in the expression for the photo-e.m.f. of the metal/semiconductor contact [11]. In the framework of the foregoing, the mechanisms of the dependences \( \Delta U_{ph}(\dot{E}) \), \( \Delta U_{ph}(I) \), \( \Delta U_{ph}(\lambda) \), \( \Delta U_{ph}(T) \) found experimentally on the studied metal/n-InSe contacts are clear and satisfactorily obey the theory of photo-e.m.f. at the metal/spatially homogeneous crystalline semiconductor contact [1, 2, 11, 12] under various conditions (in the absence and under the condition of heating the current carriers by an electric field). As for the reasons for some of the detected deviations from this theory - the dependence of the \( \Delta U_{ph} \) value and the course of the \( \Delta U_{ph}(\dot{E}) \), \( \Delta U_{ph}(T) \) curves on the initial value of the dark resistivity of n-InSe crystals at

**Figure 3.** Kinetics of \( \Delta U_{ph} \) at different values of the initial dark resistivity of n-InSe in the metal/n-InSe contact.

\( T_0=77 \) K; \( \dot{E}=5 \times 10^3 \) V cm\(^{-1}\); \( \lambda=0.95 \) \( \mu \)m; \( I=0.25 I_0; \rho_{D0} \) (\( \Omega \) cm): 1 -2 \( \times \)10\(^3\); 2 - 4 \( \times \)10\(^6\).
In conclusion, it can be noted that:

- change in the magnitude of the photo-e.m.f. on the metal/n-InSe contact when exposed to a microwave electric field with an intensity greater than a certain critical value is due to an increase in the effective temperature of free main charge carriers (electrons) when they are heated by an electric field;
- the dependences of the magnitude of the change in photo-e.m.f. on metal/n-InSe contact is experimentally found, and its characteristics from the value of the initial dark resistivity of n-InSe crystals at \( \rho_D > 3 \times 10^5 \, \Omega \cdot \text{cm} \) are associated with the presence of random macroscopic defects and the appearance, as a result of two types (drift and recombination) of barriers in them;
- influence of random macroscopic defects existing in n-InSe crystals on photo-e.m.f., upon heating free current carriers by an electric field, it gradually disappears with increasing the heating level.

References

1. Ryvkin S M 1963 *Photoelectric phenomena in semiconductors* (M.: Nauka) p 429
2. Vorob'ev L E, Danilov S N, Zegrya G G, Firsov D A, Shalygin V A, Yassievich I N and Beregulin E V 2001 *Photoelectric phenomena in semiconductors and quantum-dimensional structures* (St. Petersburg: Science) p 248
3. Vorob'ev L E, Danilov S N, Ivchenko E L, Levinstein M E, Firsov D A and Shalygin V A 2000 *Kinetic and Optical Phenomena in Strong Electric Fields in Semiconductors and Nanostructures* (St. Petersburg: Science) p 160
4. Conwell E 1970 *Kinetic properties of semiconductors in strong electric fields* (M.: Mir) p 384
5. Denis V and Pojela Y 1970 *Hoot electronics* (Vilnius: Mintis) p 314
6. Veinger A I and Abdinov A Sh 1974 *Photoelectric light detector* Copyright certificate No. 455679
7. Babayeva R F and Abdinov A Sh 2019 *Journal of Physics: Conference Series* 1400 066047
8. Babayeva R F and Abdinov A Sh 2020 *Journal of Physics: Conference Series* 1697 012065
9. Medvedeva Z S 1968 *Chalcogenides of elements III B of the subgroup of the periodic system* (M.: Nauka), p 216
10. Abdinov A Sh and Babayeva R F 2019 *Inorganic Materials* 55 758-64
11. Ambrozjak A 1970 *Design and technology of semiconductor photoelectric devices* (M.: Sov. Radio) p 392
12. Weinger A I, Kramer N I, Parisky L G and Abdinov A Sh 1972 *FTP* 6 353-59
13. Shik A Ya 1972 *JETP* 15 408-10
14. Abdinov A Sh and Babayeva R F 2018 *Semiconductors* 52 1662-68
15. Abdinov A Sh, Babayeva R F, Amirova S I, Ragimova N A and Rzaev R M 2014 *Semiconductors* 48 981-85

\( \rho_D > 3 \times 10^5 \, \Omega \cdot \text{cm} \), low \( T_0 \) and low illumination, as well as slow relaxation \( \Delta U_{ph} \) after the termination of the action of the pulse of strong electric field of the microwave, they are most likely due to the presence of random macroscopic defects (RMD) in n-InSe crystals [13]. These defects create drift and recombination barriers in n-InSe free zones. Drift barriers cause a difference in the value of \( \rho_D \) for different samples. In crystals with a larger number of RMD, the value of \( \rho_D \) is greater, and the mobility of free current carriers is lower. Therefore, in such samples at low \( T_0 \), the current carriers are heated weakly. At higher values of the electric field, light intensity, and sample temperature, the effect of drift barriers on the carrier mobility is "erased", the free charge carrier mobility increases and becomes the same in all studied n-InSe crystals [14, 15]. As a result of this, firstly, the observed dependences of the magnitude and characteristics of \( \Delta U_{ph} \) on \( \rho_D \) disappear, and secondly, the process of heating the current carriers by an electric field in the samples is enhanced. Recombination barriers at low illumination and low temperatures cause slow relaxation \( \Delta U_{ph} \). With an increase in the intensity of the light incident on the samples, as well as \( T_0 \), due to the light and temperature rectification of fluctuations of the electronic potential of n-InSe crystals, the effect of these barriers on the values and characteristics of \( \Delta U_{ph} \) in the samples also gradually disappears.