DOI 10.1007/s11182-018-1585-1

*Russian Physics Journal, Vol. 61, No. 9, January, 2019 (Russian Original No. 9, September, 2018)*

# PECULIARITIES OF KINETIC COEFFICIENTS OF SINGLE CRYSTALS OF A LAYERED *p*-GaSe SEMICONDUCTOR

**A. Sh. Abdinov**[1] **and R. F. Babaeva**[2]

UDC 621.315.592

*The dependences of the kinetic coefficients, namely, the Hall coefficient, electrical conductivity, and charge carrier mobility on the temperature, electric field strength, and doping with rare-earth elements are investigated in single crystals of p-type gallium selenide. It has been established that in the low-temperature region, these dependences have a peculiarity caused by the presence of random macroscopic defects in the samples under study. At a small level of doping of p-*GaSe *single crystals with* Gd *and* Er*, a non-monotonic dependence of the mobility and electrical conductivity on the content of the introduced impurity is observed.*

**Keywords:** doping, electrical conductivity, Hall coefficient, mobility, random macroscopic defects, impurities.

## INTRODUCTION

Gallium monoselenide (GaSe) belonging to the $A^{III}B^{VI}$ class of semiconductor compounds with a layered crystal structure attracts the attention of researchers because of its unique physical properties caused by strong anisotropy. These compounds, in addition to a variety of optical, photovoltaic, and luminescent properties that are of significant scientific and practical interest, possess important electrical properties – switching effect, low-frequency electrical instability, Frenkel effect, etc. The electrical conductivity and the Hall coefficient were studied experimentally in pure polycrystalline [1, 2] and single-crystal [3–6] *p*-GaSe samples as well as in those doped with various impurities, including rare earth elements [7–9]. However, either samples with high content of the introduced impurity were studied and measurements were carried out at temperatures, when free carrier scattering occurs on the impurity ions and phonons [7], or the effect of doping on the electrical conductivity under the conditions of monopolar injection in the mode of space-charge-limited currents (SCLC) were considered [8–10]. The main goal of the above papers [1–10] was to determine the parameters of local levels associated with the intrinsic defects and specially introduced impurities, as well as the width of the forbidden band for the semiconductor under study. In addition, in [3–6, 11, 12], when studying electrical and photoelectric characteristics of *p*-GaSe single crystals at low temperatures, it was shown that for different samples, the electrical resistivity and free charge carrier mobility differ significantly, and the experimental dependences of the kinetic coefficients on temperature, electric field strength, exposure to light, and doping differ from the known theoretical data. To date, the cause of this discrepancy has not been explained. In the present work, the dependences of the kinetic coefficients — the Hall coefficient ($R_H$), conductivity ($\sigma$), and free charge carrier mobility($\mu$) – on the temperature ($T$), electric field strength ($E$), and doping with Gd and Er are studied experimentally for *p*-GaSe single crystals and an explanation of these dependences is given.

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[1] Baku State University, Baku, Azerbaijan Republic, e-mail: abdinov-axmed@yandex.ru; [2] Azerbaijan State University of Economics, Baku, Azerbaijan Republic, e-mail: babaeva-rena@yandex.ru. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika, No. 9, pp. 102–107, September, 2018. Original article submitted January 22, 2018; revision submitted July 11, 2018.

## 1. EXPERIMENTAL

### 1.1. Materials

The synthesis of the GaSe compound was carried out by joint fusion of the composite components (Ga and Se), and the GaSe single crystals were grown from the synthesized substance by the modified Bridgman method [13]. Based on the geometrical and electrochemical factors, namely, the permissible values of the deviation of ionic radii and electronegativity of impurity atoms from those of the matrix [14], and also to prevent oxidation during the manufacture of the furnace-charge, when studying the influence the content of introduced impurity on the kinetic coefficients, two most characteristic, but differing in their physical and chemical properties heavy rare earth elements (REE) Gd and Er were used for doping [15, 16].

The structure, phase and elemental composition of the ingots obtained, the state of the surface along the plane of the natural layers (the (001) plane) of the samples under study were determined by the complex X-ray diffraction, X-ray, thermographic, X-ray spectroscopic, and microscopic analyzes. For this purpose, modern, as well as proven measurement systems and methods were applied (DSC-910, ADVNCE-8D, SINTECP 21, DRON-4-07 using Cu$K_\alpha$ radiation with a step of 0.050 and range of angles 8–135°, and the Zeiss SEM with the energy dispersion analyzer).

It is established that the obtained pure and doped single crystals are homogeneous, have *p*-type conductivity and sufficiently good monocrystalline structure, their diffraction patterns are indexed in a hexagonal syngony (of an ε-polytype) and belong to a space group $D_{3h}^1$ (or $P\overline{6}$) [1, 2, 17, 18] with the elementary cell periods $a \approx 3.744$ Å and $c \approx 15.902$ Å, no substitution phases of selenides, oxides, and free REEs are detected, and there are no heterogeneities and foreign phases on the surface of the samples under study.

Some samples were cleaved from different areas of large single crystal ingots. The values of the initial electrical resistivity at 77 K ($\rho_0$) varied within $\sim 5\cdot 10^3$–$1.5\cdot 10^7$ $\Omega\cdot$cm, and the content of the introduced impurity ($N$) in the doped crystals was $10^{-5}$, $5\cdot 10^{-5}$, $10^{-4}$, $5\cdot 10^{-4}$, $10^{-3}$, $10^{-2}$, and $10^{-1}$ at.%.

The samples under investigation had the form of a plane-parallel plate, the length (the distance between the current contacts) and transverse dimensions (the thickness in the direction perpendicular to the natural layers of the crystal and the distance between the Hall contacts arranged along the plane of the layers) were 6–8 mm and (0.30–1.00)×(2–3) mm$^2$, respectively. Both current and probe contacts created by soldering an ordinary solder (tin) without flux covered all the layers of the sample under study (Fig. 1*a*) and were ohmic under the conditions considered.

### 1.2. Research methods

The kinetic parameters were measured using the traditional three-probe method in alternating electric and magnetic fields using electric signal amplifiers. In this case, the working and Hall currents flowed along the natural layers of the crystal, and the magnetic field was directed perpendicular to these layers (Fig. 1*a*).

For the samples with various $\rho_0$ and $N$, the dependences $R_X(T)$, $\sigma(T)$, and $\mu(T)$ as well as $\sigma(E)$ and $\mu(E)$ were measured in the temperature range of 77–350 K and at electric field strengths up to the strength of the switch effect [19], respectively.

## 2. RESULTS AND DISCUSSION

It is established that in the low-temperature region ($T < 250$–280 K), the dependences $R_X(\rho_0)$, $R_X(N)$, $R_X(T)$, $\sigma(T)$, and $\mu(T)$, as well as $\sigma(N)$, $\mu(\rho_0)$, and $\mu(N)$ have an anomalous character significantly deviating from the known theoretical concepts [20]. In particular, the values of the Hall coefficient for various samples are independent of the temperature (Fig. 1*b*, curve *1*), initial electrical resistivity (Fig. 2, curve *2*), content of the introduced impurity (Fig. 3, curve *2*), and conductivity (Fig. 1*b*, curves *2–4*), the free charge carrier mobility (Fig. 1*b*, curves *5–7*) increases with increasing temperature according to the exponential law ($\sigma = \sigma_0\exp(-\Delta\varepsilon_\sigma/kT)$; $\mu = \mu_0\exp(-\Delta\varepsilon_\mu/kT)$), and the slopes of the $\sigma(T)$ and $\mu(T)$ curves for the same sample coincide with each other ($\Delta\varepsilon_\sigma = \Delta\varepsilon_\mu$).