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## Determination of light and heavy hole parameters in *p*-GaSb single crystals on the basis of complex analysis of the Hall effect

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***In this work we present the results of measurements of electrophysical parameters of commercially available single-crystal *p*-GaSb substrates in the temperature range of 80–300 K. We perform comparative analysis of temperature and field dependences of Hall resistivity with and without taking into account the degeneracy of the valence band. The limitations of applicability of the standard model, which assumes the existence of only one type of holes, for describing transport properties of *p*-GaSb are shown. It is shown that non-monotonic temperature dependence of substrates resistivity arises due to monotonic change of carrier concentrations and mobilities. Basing on the results of the analysis using model, which takes into account contributions of light and heavy holes, we estimated the variation of the chemical potential in substrate material with temperature. The obtained results are necessary for further design of photosensitive heterostructures, obtained using studied substrates.***

***Keywords:*** gallium antimonide, *p*-type conductivity, semiconductor substrates, Hall effect, magnetoresistance, multi-band semiconductors.

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### Introduction

New approaches in IR photosensorics based on antimony-containing semiconductor epitaxial A<sup>III</sup>B<sup>V</sup> heterostructures have been actively developing recently [1, 2]. When short-period superlattices are used as absorbing layers, these heterostructures cover an extremely wide spectral range, including the atmospheric transparency windows of 3–5 μm and 8–12 μm, while simultaneously providing specific detectivity close to the fundamental limit at temperatures of 80–150 K [3]. Along with the choice of heterostructure design, the substrate material used for the epitaxial growth of the structure plays a

key role in achieving high photovoltaic characteristics.

Due to the possibility of precise lattice constant matching, monocrystalline GaSb wafers of *n*- or *p*-type are among the most convenient substrates for growing photosensitive heterostructures based on superlattices is [2, 4]. Regardless of the type of photosensitive element architecture, the transport properties of the substrate inevitably affect the performance of the photosensitive elements, even when the substrates are thinned down to thicknesses of 10–20 μm. This influence is determined by two main factors: the presence of additional resistance connected in parallel to the contact layer, and band bending

caused by the alignment of the chemical potential between the substrate and the photosensitive element. To ensure reliable prediction of the operating modes of the photosensitive elements, these factors must be accounted for correctly at the heterostructure design stage. Consequently, the transport properties of substrates used for epitaxy must be studied over a wide temperature range.

This paper presents the results of electrophysical studies of epi-ready *p*-GaSb substrates manufactured by Pam Xiamen (China). These substrates are the primary *p*-type substrates with low doping levels currently available in the Russian Federation. The paper presents the results of conductivity and Hall resistance measurements in a wide temperature range, which allowed for the determination of the concentration, mobility, and chemical potential of majority carriers vs. temperature. A correct assessment of the chemical potential is achieved by using a two-band model that considers the contributions of light and heavy holes to the transport properties, and by comparing it to the results of processing within the framework of the single-band model, which is much more commonly used for the standard characterization of semiconductor materials.

### Samples and Measurement Procedure

Three *p*-type GaSb samples (T1, P1, and P2) cleaved from commercially available two-inch wafers with a thickness of 0.53 mm have been studied in this paper (Pam Xiamen, China).

For the measurements, contact pads of Ti/Au (T1) or Ti/Pd/Au (P1 and P2) were deposited on the samples. Samples T1 and P1 were cleaved from the same wafer, while sample P2 was cleaved from another one. In fact, this study considers three samples to demonstrate the reproducibility of the electrophysical characteristics and associated material parameters. To perform the measurements, the samples were mounted on a holder, and the contact pads on the holder and the sample were connected by ultrasonic bonding of an aluminum wire.

The transport and magnetotransport properties of these samples were studied on a setup based on an electromagnet in the temperature range  $T = 80\text{--}300$  K and in magnetic

fields up to  $B = 0.9$  T. The measurements were carried out using direct current switched according to a four-probe scheme. A combination of a voltage source and a reference resistor was used for the measurements; the current in the measuring circuit was measured independently.

### Findings and Discussion

The field and temperature dependences of the longitudinal ( $\rho_{xx}$ ) and Hall ( $\rho_{xy}$ ) resistances of the samples under study were measured as part of this study. Fig. 1*a–b* shows the field dependences of the Hall resistance  $\rho_{xy}$  at temperatures of 300 K and 80 K. The sign of the obtained curves indicates that conductivity is of *p*-type throughout the entire temperature range studied. Some difference can be seen between the experimental curves, which is obviously related to minor fluctuation in the properties of the wafers under study. However, as will be shown below, the corresponding difference in the transport parameter values for different samples turns out to be insignificant, thus confirming the good reproducibility of the material properties.

Hall data are often analyzed within the framework of a single-band model, where only one group of charge carriers is assumed to exist. In this case, the  $\rho_{xy}(B)$  dependence should be linear, while the concentration  $p^*$  and mobility  $\mu^*$  of the charge carriers are derived from the value of the linear slope  $R_H = d\rho_{xy}/dB$  using the standard relations:

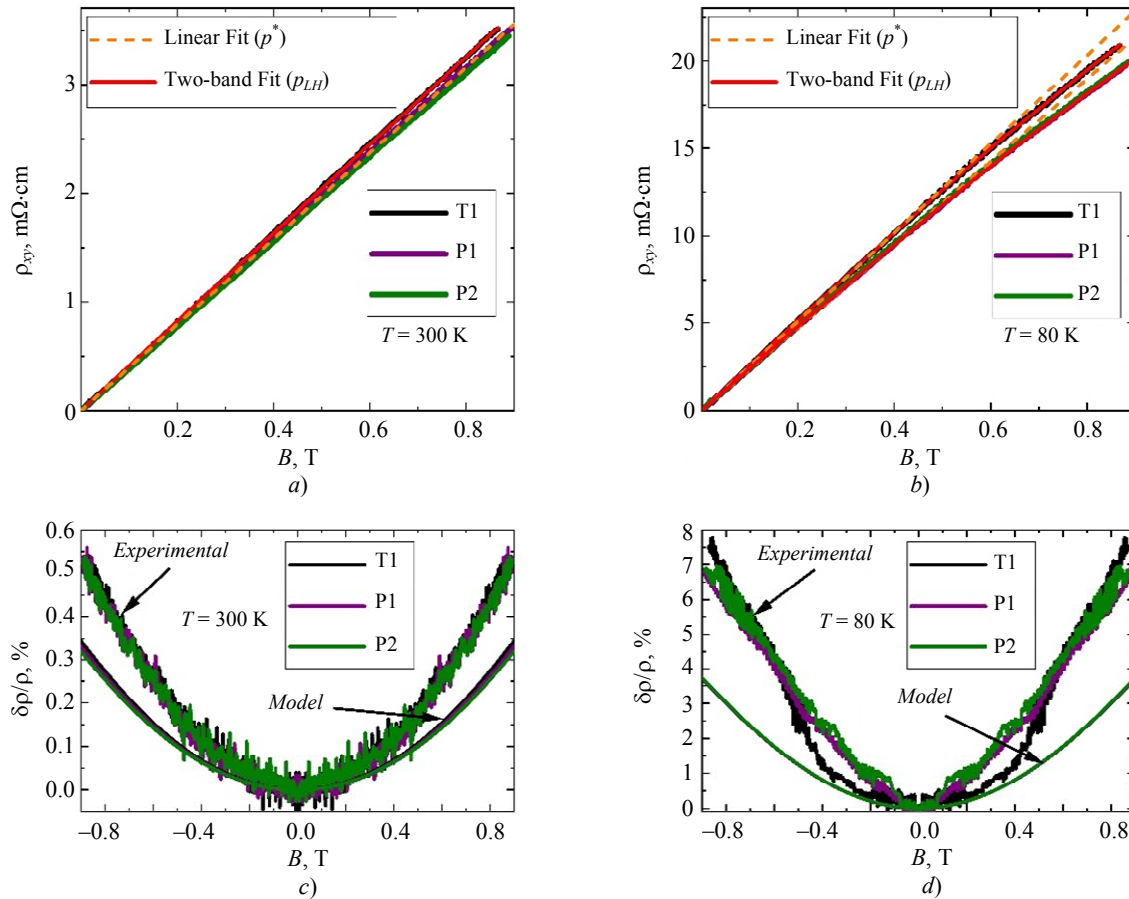
$$p^* = \frac{r_H}{eR_H}, \quad (1)$$

$$\mu^* = \frac{R_H}{r_H \rho_{xx}}, \quad (2)$$

where  $e$  is the electron charge, and  $r_H$  is the Hall factor determined by the dominant charge carrier scattering mechanism. In most cases  $r_H = 1$  is assumed. Such an analysis of  $\rho_{xy}(B)$  is often carried out in a very narrow field range and is used for the characterization of commercially available materials (including those by the manufacturer of the wafers studied herein). In our case, the linear approximation (examples are

shown by the orange dashed line in Fig. *a–b*) was performed in the range up to  $\pm 0.5$  T. As can be seen from the figures, the linear function describes the experimental data well over the entire field range at the room temperature, but a clear mismatch can be observed at low temperatures in higher fields, thereby indicating the inapplicability of the simplest model in this

case. The hole concentration and mobility values calculated using formulas (1) and (2) are presented in Table 1. Even these results prove that a temperature decrease is accompanied by a significant decrease in the charge carrier density and an increase in their mobility. The obtained values correspond well to the certified values stated by the wafer manufacturer.



**Fig. 1.** Field dependences (*a, b*) of the Hall resistance and (*c, d*) of the magnetoresistance of the samples under study at temperatures of (*a, c*) 300 K and (*b, d*) 80 K. In figures (*a, b*), the orange dashed line shows the linear approximation of the data in the range up to  $\pm 0.5$  T, and the red line shows the approximation of the data using the two-band model (7–8). In addition to the experimental data, figures (*c, d*) show the magnetoresistance model curves calculated using formulas (7–10) with the parameter values listed in Table 1

**Table 1**

**Transport parameters of the samples under study at the temperatures of 300 K and 80 K: resistivity  $\rho_{xx}$ , hole concentrations and mobilities ( $p^*$  and  $\mu^*$ ) obtained within the framework of the single-band model (1–2), and parameters of light (LH) and heavy (HH) holes calculated using the two-band model (7–8) at  $K_n = 22.6$ ,  $K_\mu = 0,1$**

| Sample    | $T$ , K | $\rho_{xx}$ ,<br>mΩ·cm | $p^*$ ,<br>$\times 10^{16}$ cm $^{-3}$ | $\mu^*$ ,<br>cm $^2$ /(V·s) | $p_{LH}$ ,<br>$\times 10^{16}$ cm $^{-3}$ | $\mu_{LH}$ ,<br>cm $^2$ /(V·s) | $p_{HH}$ ,<br>$\times 10^{16}$ cm $^{-3}$ | $\mu_{HH}$ ,<br>cm $^2$ /(V·s) |
|-----------|---------|------------------------|----------------------------------------|-----------------------------|-------------------------------------------|--------------------------------|-------------------------------------------|--------------------------------|
| <b>T1</b> | 300     | 68.75                  | 15.3                                   | 590                         | 1.76                                      | 1580                           | 39.8                                      | 158                            |
|           | 80      | 125.4                  | 2.46                                   | 2030                        | 0.279                                     | 5480                           | 6.29                                      | 548                            |
| <b>P1</b> | 300     | 68.14                  | 15.8                                   | 580                         | 1.81                                      | 1550                           | 41.0                                      | 155                            |
|           | 80      | 117.0                  | 2.63                                   | 2030                        | 0.299                                     | 5480                           | 6.76                                      | 548                            |
| <b>P2</b> | 300     | 68.15                  | 16.1                                   | 570                         | 1.85                                      | 1520                           | 41.8                                      | 152                            |
|           | 80      | 117.4                  | 2.61                                   | 2040                        | 0.297                                     | 5500                           | 6.71                                      | 550                            |

The deviation from the linear dependence of  $\rho_{xy}(B)$ , in the absence of a magnetic component in the system, is usually associated with the presence of several groups of charge carriers, which is typical for  $p$ -type  $A^{III}B^V$  semiconductors, due to the existence of light-hole (LH) and heavy-hole (HH) bands in their structure. In the general case, each group of carriers makes an additive contribution to the corresponding conductivity tensor components  $\sigma$  as functions of the magnetic field  $B$ :

$$\sigma_{xx}(B) = \sum_i \frac{en_i\mu_i}{1 + \mu_i^2 B^2}, \quad (3)$$

$$\sigma_{xy}(B) = \sum_i \frac{en_i\mu_i \cdot \mu_i B}{1 + \mu_i^2 B^2}, \quad (4)$$

where  $n_i$  and  $\mu_i$  are the concentration and mobility of carriers in  $i$ -band. In the case of  $p$ -type GaSb,  $i=2$ , and the parameters of the heavy-hole band can be determined through the corresponding proportionality coefficients:

$$K_n = \frac{p_{HH}}{p_{LH}}, \quad (5)$$

$$K_\mu = \frac{\mu_{HH}}{\mu_{LH}}, \quad (6)$$

Then the original components of the conductivity tensor can be rewritten in the following form:

$$\sigma_{xx} = ep_{LH}\mu_{LH} \left( \frac{1}{1 + \mu_{LH}^2 B^2} + \frac{K_n K_\mu}{1 + K_\mu^2 \mu_{LH}^2 B^2} \right), \quad (7)$$

$$\sigma_{xy} = ep_{LH}\mu_{LH}^2 B \left( \frac{1}{1 + \mu_{LH}^2 B^2} + \frac{K_n K_\mu}{1 + K_\mu^2 \mu_{LH}^2 B^2} \right). \quad (8)$$

Accordingly, the experimentally measured field dependences of resistances  $\rho_{xx}$  and  $\rho_{xy}$  can be described within the framework of the two-band model using formulas (7–8) via the corresponding inversion of the conductivity tensor components, which is written for an isotropic material in the following form:

$$\rho_{xx}(B) = \frac{\sigma_{xx}(B)}{\sigma_{xx}^2(B) + \sigma_{xy}^2(B)}, \quad (9)$$

$$\rho_{xy}(B) = \frac{\sigma_{xy}(B)}{\sigma_{xx}^2(B) + \sigma_{xy}^2(B)}. \quad (10)$$

It is quite obvious that the actual shape of the theoretical curves is determined by the values of  $\mu_{LH}$ ,  $K_n$  and  $K_\mu$ , while the value of  $p_{LH}$  is simply a scaling factor. Nevertheless, the approximation of a single curve  $\rho_{xy}(B)$  with a function containing four fitting parameters can lead to noticeable ambiguities in the results obtained, especially in a limited magnetic field range. Therefore, in some cases, it is recommended to perform a simultaneous approximation of curves  $\rho_{xy}(B)$  and  $\rho_{xx}(B)$  with a single set of parameters. The applicability of this approach requires the presence of a contribution only from the classical magnetoresistance (MR) mechanism described by formula (9). However, most materials exhibit contributions from several MR mechanisms, for example, the amplitude of the linear MR contribution can exceed that of the classical mechanism by orders of magnitude [5]. Thus, the recording of data of  $\rho_{xx}(B)$  can significantly increase the error in the results obtained. Therefore, a more convenient way to improve the accuracy of the Hall data approximation within the framework of the two-band model is to consider the zero-field resistance, which in the case of  $p$ -GaSb is written as:

$$\rho_{xx}(B=0) = \frac{1}{ep_{LH}\mu_{LH}(1 + K_n K_\mu)}. \quad (11)$$

It is easy to see that when the ratio  $\rho_{xy}/\rho_{xx}(B=0)$  is used, the dependence on  $p_{LH}$  disappears, which somewhat simplifies the fitting procedure without introducing additional errors. Therefore, in this paper, curves  $\rho_{xy}/\rho_{xx}(B=0)$  were first approximated, and then the parameters obtained were used to approximate curves  $\rho_{xy}(B)$  and to determine the values of  $p_{LH}$ .

For  $A^{III}B^V$  semiconductors, both in the case of degenerate and non-degenerate statistics, the concentrations of free charge carriers in the light-hole and heavy-hole bands turn out to be proportional to each other with  $K_n = (m_{HH}^* / m_{LH}^*)^{3/2}$ , where  $m_{HH}^*$  and  $m_{LH}^*$  are the effective masses of heavy and light holes. For GaSb, the corresponding values vary somewhat in the literature [6–9], but this paper uses value  $1/\gamma_m = m_{HH}^* / m_{LH}^* = 8$  [10]. Accordingly, we can assume  $K_n \approx 22.6$ , without considering band nonparabolicity effects of the bands (which is justified in the case of low charge carrier densities). Since the temperature dependence of effective masses in classical semiconductors is rather weak [11], this value of  $K_n$  can be assumed constant over the temperature range under consideration. In turn, based on the ratio of effective masses  $\gamma_m$ , one may expect  $K_\mu \sim \gamma_m = 0,125$  in the case of GaSb under the condition of equal relaxation times for the two types of holes. However, since such an assumption seems unjustified, the value of  $K_\mu$  was determined from the approximation of the low-temperature data (Fig. 1b), as a result of which the average value was taken to be  $K_\mu = 0,1$ . The data at room temperature (Fig. 1a) are almost linear, for which reason independent determination of  $K_\mu$  is impossible in this case; therefore, value  $K_\mu = 0,1$  was used over the entire temperature range under consideration. It is worth noting that the actual ratio  $K_\mu$  is determined by summing the contributions from various scattering mechanisms [12]; for example, in the simplest case, scattering by longitudinal acoustic phonons implies  $K_\mu \sim \gamma_m^{5/2} \approx 0,0055$ , while scattering by ionized impurity atoms implies  $K_\mu \sim \gamma_m^{1/2} \approx 0,354$ . Thus, a more detailed analysis of the value of  $K_\mu$  and its possible variation over a wider temperature range can provide valuable information about the evolution of the contributions of different charge carrier scattering channels, which, however, is beyond the scope of this paper.

The described approximation algorithm allowed us to achieve good alignment of experimental curves with model curves (shown

by red lines in Fig. 1a–b) over the entire magnetic field range. The approximation parameters obtained are presented in Table 1. It can be seen that the concentration values  $p^*$  and  $p_{LH}$  differ by almost an order of magnitude. In principle, value  $p^*$ , which is often used for the characterization of  $p$ -type  $A^{III}B^V$  semiconductors, is a kind of mathematical abstraction, since the ratio  $p^* / p_{LH}$  depends on the parameters  $\mu_{LH}$ ,  $K_n$  and  $K_\mu$  significantly. Thus, the value  $p^*$  can only be used as a derived parameter for analyzing the effect of small modifications of the material (when comparing samples with each other), while a more systematic study requires analysis within the framework of model (7–10).

Fig. 1c–d shows the MR curves for the samples under study, which were determined in the standard way:

$$\frac{\delta\rho}{\rho} = 100\% \times \frac{\rho_{xx}(B) - \rho_{xx}(B=0)}{\rho_{xx}(B=0)}. \quad (12)$$

It can be seen from the figure that the samples exhibit a positive MR amounting to approximately 0.52% at the room temperature (Fig. 1c), and about 7% at the liquid nitrogen temperature (Fig. 1d). In principle, the observed MR indicates a significant role of the classical MR mechanism, and its amplitude increase upon cooling is associated with the accompanying growth of the charge carrier mobility. For verification purposes, model MR curves with the parameter values listed in Table 1 were obtained based on formulas (7–10). The corresponding curves are also shown in Fig. 1c–d. It is clearly seen that the model curves have a smaller amplitude compared to the experimental data at both temperatures. Such a discrepancy is indicative of additional contributions from other MR mechanisms in the samples under consideration.

Then, the temperature dependences of the resistance tensor components of the samples under study were analyzed. Fig. 2a shows the dependences of  $\rho_{xx}(T)$  in a zero magnetic field. It can be seen that the dependence is non-monotonic: a metallic character at high temperatures changes to a semiconductor one below about 170 K. Further cooling to 80 K

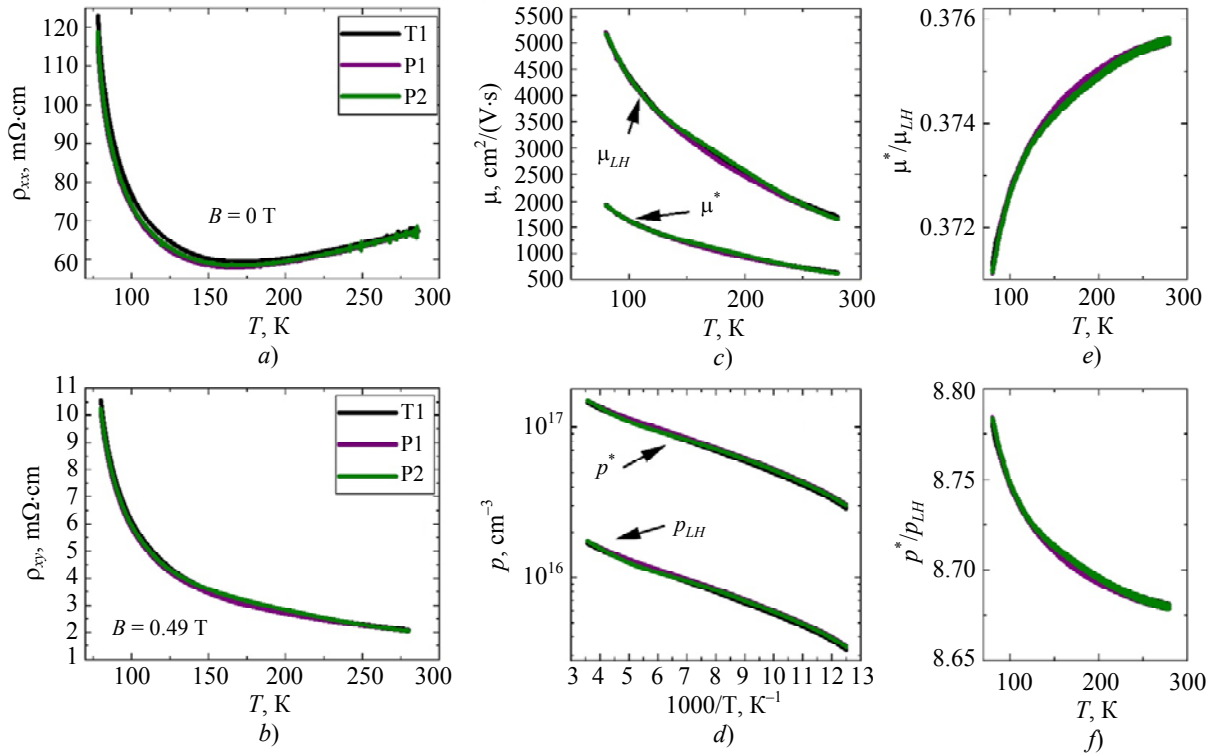
causes the resistance to increase by approximately a factor of two. This character of the  $\rho_{xx}(T)$  curves suggests the presence of competing contributions to the temperature variation of the system conductivity. To visualize them, the temperature dependence of the Hall effect in a constant magnetic field was measured. In this case, two curves were measured at different field polarities, after which an antisymmetrization procedure was applied to the curves (to eliminate the parasitic contribution of the longitudinal resistance in the signal associated with the asymmetry of the Hall contacts). The resulting curves  $\rho_{xy}(T)$  are shown in Fig. 2b.

As can be seen from the figure, in contrast to the  $\rho_{xx}(T)$  curves, the amplitude of the Hall effect in the samples under study exhibits a strictly monotonic temperature dependence that indicates a decrease in the free charge carrier concentration upon cooling, which is characteristic of a non-degenerate semiconductor.

Similarly to the analysis of the field dependences, the temperature dependences of the hole concentrations and mobilities can be determined both within the framework of the single-band model (1–2) (curves  $p^*(T)$  and  $\mu^*(T)$  were obtained by this method) and within the framework of the two-band model (7–10). However, a number of complications arise in the latter case. In contrast to the analysis of curves  $\rho_{xy}(B)$ , in the case of temperature dependences, it is impossible to approximate the experimental curve without assuming a specific form (model) for the temperature dependence of the concentrations and mobilities of the charge carriers in both bands (which could be described by a finite set of parameters). Technically, general models can be applied for known systems quite successfully; however, in our case, the objective of the analysis is to determine the form of the dependences  $p_{LH}(T)$  and  $\mu_{LH}(T)$ . Therefore, the analysis within the framework of the two-band model practically reduces to solving

the system of equations (7, 8, 10) at each point of dependence  $\rho_{xy}(T)$ . For this purpose, by means of the values of  $K_n$  and  $K_\mu$  employed in the analysis of the field data, the modulus of the difference between the experimental values of  $\rho_{xy} / \rho_{xy}(B=0)$  and the theoretical expression for this quantity was minimized for the corresponding quantity. The theoretical values were obtained by substituting (7–8) into (10) and dividing by (11)). This minimization was carried out using standard methods in the Python environment, in particular, using the “Nelder-Mead” algorithm from the SciPy library). Thus, the curves  $\mu_{LH}(T)$  were obtained, from which (using the known  $K_n$  and  $K_\mu$ ) the curve  $p_{LH}(T)$  was calculated from the data  $\rho_{xx}(T, B=0)$ , and then the curves for the heavy-hole band were calculated. It should be noted here that, under the assumptions used, the latter are completely identical to the curves for light holes (up to a constant factor), and therefore are not presented here.

Fig. 2c shows the temperature dependences of the hole mobilities calculated within the single-band and two-band models. It is clearly seen that the character of all dependences is strictly monotonic and corresponds to a mobility decrease upon warming, with no significant qualitative difference observed between the curves obtained within different models. It is important to note that the latter may be partly due to the choice of the magnetic field magnitude during measurement of  $p_{xy}(T)$ , since, as noted above, in fields up to 0.5 T the dependences of  $p_{xy}(B)$  appear to be nearly linear. Accordingly, when measuring  $p_{xy}(T)$  in higher magnetic fields or down to lower temperatures (where the nonlinearity of  $p_{xy}(B)$  begins to manifest in lower fields), the differences between the single-band and two-band models are expected to become more noticeable.



**Fig. 2.** Temperature dependences of (a) resistivity and (b) Hall resistance in a fixed magnetic field for the studied samples. Temperature dependences of (c) mobilities and (d) hole concentrations calculated within the single-band and two-band models. Temperature dependences of ratios of (e) mobilities and (f) hole concentrations obtained within the two models

The general shape of the temperature dependences of the hole mobilities in Fig. 2c is typical for non-degenerate semiconductors and is usually described by a superposition of scattering contributions from phonons and ionized impurity atoms [13]. Accordingly, the mobility increase upon cooling is attributed to decreasing phonon occupation numbers and a reduced fraction of ionized impurities (due to the return of electrons from the acceptor level to the valence band). In general, additional features may be associated with different types of screening of the impurity potential by charge carriers, the presence of a significant contribution from optical phonon scattering [14], as well as the existence of minority charge carriers and the associated electron-hole scattering [15].

Fig. 2d shows the curves of  $p_{LH}(T)$  in comparison with the curves of  $p^*(T)$  obtained within the single-band model. It can be seen from Fig. 2d that the character of the concentration dependences is also qualitatively similar. At the same time, the deviation from the linear character of the curves in the presented coordinates suggests that several impurity levels exist in the

wafers under study (since the concentration of intrinsic charge carriers in GaSb in the temperature range under consideration does not exceed  $10^{12} \text{ cm}^{-3}$ ). Thus, the non-monotonic character of the initial  $\rho_{xx}(T)$  curves is determined by the monotonic changes in the concentration and mobilities of the charge carriers along with temperature.

It is important to note that despite the similarity of the curves obtained within the single-band and two-band models, a more detailed analysis of the temperature dependences of the ratios  $\mu^*/\mu_{LH}$  and  $p^*/p_{LH}$  shown in Figs. 2e–f proves that even in our case, the values vary somewhat along with the temperature, i.e. the curve shapes turn out to be different. This difference can be much more noticeable if coefficients  $K_n$  and  $K_\mu$  change along with the temperature. Therefore, the results obtained within the single-band model may, in the general case, not only be numerically incorrect but also introduce significant distortion into the determined change of transport parameters with temperature. This becomes essential for the subsequent analysis of such dependences, for

example, for estimating energies of impurity levels in the system.

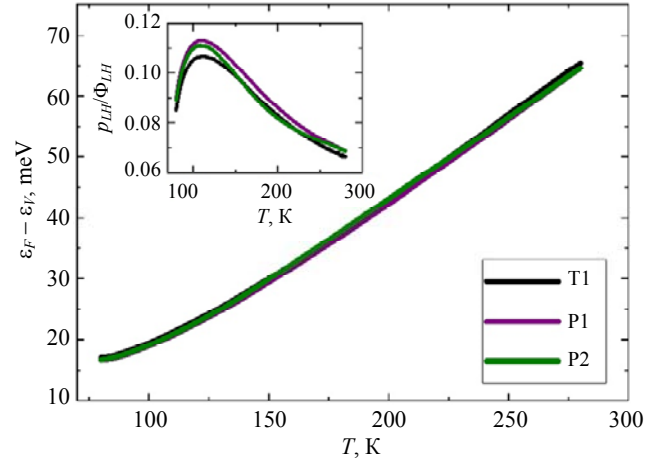
A much more obvious limitation of the single-band model is the lack of a simple relationship between the obtained values and the actual parameters of a multiband semiconductor. In particular, to estimate the chemical potential (position of the Fermi level  $\varepsilon_F$  relative to the valence band top  $\varepsilon_V$ ) in a  $p$ -type semiconductor, the standard expression is used [16]:

$$\varepsilon_F(T) - \varepsilon_V = -kT \cdot \ln(p(T)/\Phi_V(T)), \quad (13)$$

where  $p$  is the free hole concentration, and  $\Phi_V(T)$  is the density of states in the valence band, which is calculated (in units of  $\text{m}^{-3}$ ) as

$$\Phi_V(T) = 4.83 \cdot 10^{21} \cdot \left( T \frac{m^*}{m_e} \right)^{3/2}, \quad (14)$$

where  $m^*$  is the density-of-states effective mass of carriers in the band, and  $m_e$  which depends on the free electron mass. Accordingly, when the data  $p^*(T)$  obtained within the single-band model are used, quantity  $m^*$  loses its meaning as an effective mass and becomes a “gauge” constant, i.e., a fitting parameter, and cannot be estimated independently without applying the two-band model. In turn, there is no such problem for the  $p_{LH}(T)$  curves, since in this case one can use the tabulated value of  $m_{LH}^* = 0.05m_e$  [7, 8, 10]. The result of the corresponding calculation is shown in Fig. 3, and the inset shows the change of the degeneracy factor  $p_{LH}(T)/\Phi_{LH}(T)$  along with the temperature. For the samples under study, the ratio  $p_{LH}(T)/\Phi_{LH}(T)$  does not exceed 0.12, this confirming the applicability of non-degenerate statistics for describing the studied wafers (classical criterion  $\leq 0.15$  [16]). In its turn, the chemical potential (Fig. 3) shifts toward the middle of the bandgap upon warming, which is typical for an extrinsic semiconductor.



**Fig. 3. Temperature dependence of the chemical potential position measured from the valence band top for the samples under study. The inset shows the change of degeneracy factor  $p_{LH}(T)/\Phi_{LH}(T)$  along with the temperature**

## Conclusion

This paper presents a study on the magnetotransport properties of commercially available  $p$ -GaSb wafers. The temperature dependence of the sample resistance was shown to be non-monotonic, resulting from the monotonic changes in the underlying transport parameters. The Hall effect analysis was performed both within the framework of the standard single-band model and considering the existence of both light-hole and heavy-hole bands. An algorithm for data processing within the two-band model has been described. The values of the hole concentrations and mobilities obtained within the two models turned out to be significantly different. Furthermore, the proportionality coefficient between the corresponding results depends on a number of system parameters and cannot be calculated independently. From the temperature dependence of the charge carrier concentration calculated within the two-band model, the change of the chemical potential along with temperature has been determined. Since the position of the substrate's chemical potential determines the band bending for a layer grown on it, the obtained values of  $\varepsilon_F(T)$  can be used for further design of heterostructures based on epi-ready  $p$ -GaSb substrates manufactured by Pam Xiamen (China).

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